

SPECIAL PUBLICATION 110

# 29th FORUM ON THE GEOLOGY OF INDUSTRIAL MINERALS: PROCEEDINGS

1995



DEPARTMENT OF  
CONSERVATION

Division of  
Mines and Geology

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**COVER PHOTO:**

U.S. Borax open-pit borate mine, Boron, California.  
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**SPECIAL PUBLICATION 110**

# **29th Forum on the Geology of Industrial Minerals: Proceedings**

**LONG BEACH, CALIFORNIA  
APRIL 25-30, 1993**

**DAVID J. BEEBY, CHAIRMAN**

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and  
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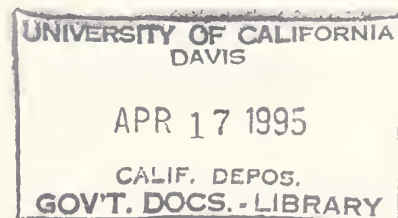
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Division of Mines and Geology**

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## ANNUAL MEETINGS OF THE FORUM ON THE GEOLOGY OF INDUSTRIAL MINERALS

1st	1965	Columbus, Ohio
2nd	1966	Bloomington, Indiana
3rd	1967	Lawrence, Kansas
4th	1968	Austin, Texas
5th	1969	Harrisburg, Pennsylvania
6th	1970	Ann Arbor, Michigan
7th	1971	Tampa, Florida
8th	1972	Iowa City, Iowa
9th	1973	Paducah, Kentucky
10th	1974	Columbus, Ohio
11th	1975	Kalispell, Montana
12th	1976	Atlanta, Georgia
13th	1977	Norman, Oklahoma
14th	1978	Albany, New York
15th	1979	Golden, Colorado
16th	1980	St. Louis, Missouri
17th	1981	Albuquerque, New Mexico
18th	1982	Bloomington, Indiana
19th	1983	Toronto, Ontario
20th	1984	Baltimore, Maryland
21st	1985	Tucson, Arizona
22nd	1986	Little Rock, Arkansas
23rd	1987	North Aurora, Illinois
24th	1988	Greenville, South Carolina
25th	1989	Portland, Oregon
26th	1990	Charlottesville, Virginia
27th	1991	Banff, Alberta
28th	1992	Martinsburg, West Virginia
29th	1993	LONG BEACH, CALIFORNIA

### NOTICE

These reports have been published essentially as received. They have been edited only to achieve consistency within an individual paper. References were not checked for completeness or accuracy. Readers are directed to the authors for further information or clarification of data.

# CONTENTS

PAGE

PREFACE.....	vii
--------------	-----

ACKNOWLEDGMENTS .....	ix
-----------------------	----

## GENERAL TOPICS

Communication in Diversity	
Robert L. Bates .....	1
Biotechnology and Industrial Minerals	
Nelson R. Shaffer .....	5
Intravenous Geology	
Bobby J. Timmons .....	17
Flake Graphite and Zeolite Research Provides Potential Solutions to Domestic Problems	
L.J. Nicks, L.E. Schultze, E.G. Valdez .....	21

## EASTERN UNITED STATES

Waste Material Resources in Virginia	
Palmer C. Sweet .....	29

## WESTERN UNITED STATES

Production and Marketing of Perlite in the Western United States	
George S. Austin and James M. Barker .....	39
Geology of Western U.S. Talc Deposits	
Richard B. Berg .....	69
1992 Industrial Mineral Production in California and Nevada	
Fred V. Carrillo .....	81
Limestones of New Mexico and Adjoining Areas Suitable for Sulfur Removal in Coal-Fired Power Plants	
Frank E. Kottowski and Augustus K. Armstrong .....	87

## CALIFORNIA

Mineral Land Classification in California	
Ralph Loyd, Robert Hill, and Russell Miller .....	101
California Mineral Education Foundation Conference Model: Changing Public Perception of the Mineral Industries	
Greg R. Wheeler .....	113
Pumice for Stone-washed and Acid-washed Textiles: Benton Pumice Beds, Mono County, California	
Gregg Wilkerson and Jerry Hoffer .....	119
Geology, Genesis and Mining of High Brightness, High Purity Limestone Deposits in the San Bernardino Mountains and Mojave Desert Area of Southern California	
Howard Brown .....	123
Geology, and Processing Facility, CalMat Co. Reliance Plant, Irwindale, California	
Edward D. Elkins and Thomas E. Wiegert .....	137
The Soledad Canyon Ilmenite Mine (P.W. Gillibrand Co.) San Gabriel Mountains, Southern California	
John C. Heter .....	145
Diatomaceous Earth Operation, Grefco, Inc., Lompoc, California	
David Jenkins .....	155
The Geology and Economic Development of Searles Lake	
Gail Moulton and Ken Santini .....	161

	PAGE
Geology and Mining of the Miocene Fish Creek Gypsum in Imperial County, California Roger D. Sharpe and Greg G. Cork .....	169
The Boron Open-Pit Mine at the Kramer Borate Deposit Joe W. Siefke .....	181
Geology of the Hector Mine Deposit R.D. Willette .....	189
The Mojave Desert Province, Southern California: Geologic Overview M.O. Woodburne .....	195
<b>OREGON</b>	
Brine Mineral Occurrence in the Diablo Mountain Study Area, Oregon, and its Possible Significance to Pacific Rim Trade Thomas J. Peters, Dennis S. Kostick, and Michael F. Diggles .....	223
<b>CANADA</b>	
30th Forum on the Geology of Industrial Minerals: Nova Scotia/New Brunswick, Canada John H. Fowler and Timothy C. Webb .....	241
Wollastonite in Québec Province, Canada Claude Hébert and Henri-Louis Jacob .....	245
Diamonds In Canada: An Overview Of Current Developments Robert Irvine and M. Boucher .....	253
Canada's Zero Effluent Potash Mine Brian V. Roulston .....	261
<b>MEXICO</b>	
MEXICO: Opportunities in Industrial Minerals Armando Alatorre, Peter Harben, Hal McVey, and Ken Santini .....	269
APPENDIX 1: Poster Abstracts .....	313
APPENDIX 2: List of Registrants .....	347



## PREFACE

This Proceedings Volume for the 29th Forum on the Geology of Industrial Minerals is dedicated to the memory of Bob Bates, the founder and guiding leader of the annual Forum on the Geology of Industrial Minerals, as well as a good friend. Bob was an active participant in the 29th Forum, though his death on June 21, 1994 prevented his seeing this volume in print.

When I attended my first forum more than a decade ago, Bob collared me on one of the field trips, telling me how glad he was to finally see a California representative at the meeting, and making me feel very welcome (as was always Bob's style). Not one to beat around the bush, he then asked me when California would be willing to host the group. As the state with both the highest annual dollar value of industrial mineral production, as well as the greatest diversity of types of industrial minerals produced, Bob recounted, it was time that the Forum moved west to observe some of our mineral deposits and mines. Being new to the Forum and very much in awe of Bob for his many and varied contributions to geology and to the study of industrial mineral deposits, I found it difficult to say no. Bob's logic seemed to me to be impeccable — California routinely does lead the country in diversity and dollar value of industrial mineral production. Not knowing exactly what would be involved, or what support I might find upon returning home, I told Bob I'd look into it. Upon my return to Sacramento, and fortunately for me, when I raised the possibility of Bob's inquiry, State Geologist Jim Davis and the management of our Department of Conservation fully embraced the idea. This volume, then, represents the culmination of that distant conversation with Bob.

The 29th Forum on the Geology of Industrial Minerals was held at the Long Beach Sheraton Hotel in Long Beach, California, from April 25 through April 30, 1993. The meeting was co-hosted by the California Department of Conservation's Division of Mines and Geology and the U.S. Bureau of Mines. Supplemental financial and logistical support came from the Society of Economic Geologists Foundation and 14 California mining companies, whose names are listed on the following page. Without the productive partnership of State and Federal government, professional societies, and private enterprise, the Forum and this volume would have been impossible. Their help and financial support are gratefully acknowledged.

The 29th Forum was attended by 151 participants from 25 U.S. states, six Canadian provinces, six countries, and four continents, making it a true international event. Half the participants worked for the mining industry, with 45 percent from various governmental agencies and 5 percent from academic institutions. The meeting focused on field visits to major industrial mineral producers in southern California and consisted of 2 days of technical sessions interspersed with 3 days of field trips. This proceedings volume contains papers and abstracts of presentations given at the Forum. Editing was limited to assure conformity with the proceedings format.

Much of the 29th Forum emphasized the world-class industrial mineral deposits in southern California, but industrial minerals in other states such as Arizona, Florida, Georgia, Idaho, Illinois, Minnesota, Mississippi, Missouri, Montana, Nevada, New Mexico, Oregon, Pennsylvania, Tennessee, Texas, Virginia, and Washington, and industrial minerals in Canada and Mexico were also discussed.

Participants were able to choose among five optional field trips; three field trips were 1 day in duration and two were 2 days in duration. The following southern California mines were included in these field trips: the Celite Corporation and Grefco Incorporated diatomite mining operations, Lompoc; the Mitsubishi Cement Corporation limestone mine and cement plant, Lucerne Valley; aggregate mining at the CalMat Company and Livingston-Graham Incorporated operations, Irwindale; the P.W. Gillibrand Company aggregate/anorthosite mining and ilmenite recovery operation, Soledad; the North American Chemical Company Searles Lake operation (recovery of sodium, potassium, and boron compounds from brines), Trona; the Rheox Incorporated hectorite clay mining operation, Newberry Springs; and the U.S. Borax Inc. borate mining operation, Boron. The cooperation and generosity of these mining companies who graciously opened their mines to us for field trips is especially appreciated.

The host state and provincial geological surveys from previous Forums know better than most what is involved in successfully putting on a meeting of this size. As the 1993 Forum Chairman I am grateful for the strong support not only from my Department Director and State Geologist, but also by an energetic and able Minerals Program staff within the Division of Mines and Geology. While many helped in various tasks, specific thanks and acknowledgements are due to the members of the 29th Forum Committee — Ralph Loyd, who handled logistics and organizational details of the meeting; Russ Miller, who developed the technical sessions; Chris Higgins who organized the poster sessions; Bob Hill, who planned and arranged the field trips; Don Dupras and Marialena Tabilio who compiled and edited this volume; and Mike Silva who maintained the computerized registration and financial records for the Forum. Venice Huffman, Shavonda Rhodes, and Virginia Hoskins were of great assistance with on-site registration activities and participant assistance during the meeting.

The field trips were highly praised by participants, and this should be directed to field trip leaders Al Barrows, Steve Bezore, Ron Churchill, Don Dupras, Chris Higgins, Susan Kohler-Antablin, Cindy Pridmore, Dinah Shumway, Mike Silva, and Gary Taylor. Acknowledgement is also due to the preparers of artwork and illustrations for both the Forum itself and this proceedings volume — Max Flannery, Ed Foster, Ed Kiessling, Debbie Maldonado, Ross Martin, Frances Rubish, Joy Sullivan, Jeff Tambert, Peggy Walker, Dave Wagner, Kendra West, and Jim Williams.

And finally, special thanks are extended to all forum speakers and authors who took the time and effort to prepare the articles presented in this proceedings volume.

David J. Beeby, Principal Geologist  
California Department of Conservation,  
Division of Mines and Geology  
29th Forum Chairman

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Special thanks to the Society of Economic Geologists Foundation, Incorporated, for its continued support of the Forum.

The staff of the Minerals Program of the Division of Mines and Geology wish to extend special thanks to 29th Forum Chairman, David J. Beeby, for his dedication and efforts in bringing the 29th Forum to California and his coordination of this unique event. The 29th Forum provided the opportunity for attendees to focus on the geology of industrial mineral deposits in a professional, but singularly informal, setting. This encouraged learning and open exchange of ideas among a diverse group of geologists, mining engineers, and other industrial mineral specialists from academia, private industry, and government.







# Communication in Diversity

by  
Robert L. Bates<sup>1</sup>

## ABSTRACT

The field of industrial minerals and rocks includes such a wide diversity of materials and occurrences that communication is essential to foster a sense of "belonging" among geologists and other professionals. Besides, exchange of ideas and information is essential in meeting the needs of an ever-expanding world economy. A survey of the field shows to what an extent such communication--especially in the form of conferences and their proceedings--has increased during the past 25 years.

## INTRODUCTION

It is convenient to view the field of industrial minerals and rocks as a band or spectrum. At one end is exploration for new deposits, at the other end is the use of a product. In between are mining/quarrying, crushing/grinding, sizing, and perhaps such processes as magnetic or air separation and flotation. All these prepare the mined material for use. Note the difference in this scenario from that of the metals. At a copper mine, the stuff mined is an ore; at a limestone mine, the stuff mined is the product. Even in the disassembly line at a feldspar operation, there is no smelting stage: the product is a mineral as found in nature. The geologist at the copper mine has no interest in what is done with the refined metal, but his opposite number at the stone or mineral company must be concerned with the material produced.

So it is natural that industrial-minerals people, from geologists to product analysts, tend to take a wide view of their field. Meetings may include papers on such topics as geology of a deposit, an environmental problem, permitting requirements, expanding markets, enhanced processing, quality control, and so on. All these are parts of the productive spectrum.

The field as a whole needs more favorable communication - a better image - among the other industrial fields, to say nothing of the general public. But in this paper I bypass these matters. My subject here is intra-field: how we communicate among ourselves, mainly in terms of meetings and publications. We are much more communicative today than a few decades, or even a few years, ago.

## THE INDUSTRIAL MINERALS DIVISION OF THE SME

Until the 1960s, the annual meeting of this organization was where most of the action was. But the action was often modest, because the Industrial Minerals Division was under something of a handicap. The SME<sup>2</sup> was afflicted with the metallic mentality, in which most mining involves metals or coal. Hence industrial-minerals people were somewhat in the position of stepchildren. Although small groups of engineers and geologists kept the Division going, in some years the meetings seemed to have been scheduled more from a sense of duty than from interest in the Division's subject. Recent years have seen increased interest. The 1993 meeting at Reno, for example, included 40 papers. A few were on geology, but most, naturally enough, were on topics toward the applications end of the spectrum.

In 1988 the SME abandoned its long-standing fall meetings and started a series of "regional topical conferences." Several of these have dealt with industrial minerals, for example meetings on fibers and on fine grinding in 1989, and on regulation of crystalline silica in 1990.

Over the years the SME has sponsored the standard reference work in our field: the invaluable volume *Industrial Minerals and Rocks*. Earlier editions under the editorship of Joe Gillson, then the 4th and 5th editions edited by Stan Lefond, have been the books we reached for when in need of authoritative information. The 6th edition, under Don Carr, will carry on this fine tradition. We should not forget what a tremendous debt we owe to

<sup>1</sup>Robert L. Bates, 180 Canyon Drive, Columbus, OH 43214-3106

<sup>2</sup>When the Society of Mining Engineers, Inc. changed its name in 1989 to Society of Mining, Metallurgy, and Exploration, Inc., the original abbreviation SME was retained.

the scores of experts whose volunteer efforts have made *Industrial Minerals and Rocks* our prime reference work.

*Mining Engineering*, the SME's monthly publication, is hospitable to papers on industrial rocks and minerals, especially if the papers are oriented toward production or application. The magazine's annual review of the field is a useful source of information.

## THE FORUM ON GEOLOGY OF INDUSTRIAL MINERALS

In 1965, several of us at Ohio State University decided to host what we called a Midwest Forum on Geology of Industrial Minerals. It was our idea to see whether there was enough interest in the subject to make such a meeting worthwhile. Although the first Forum convened in the teeth of a February blizzard, more than 75 persons showed up and it was clear that a need existed. An offer from Indiana University for a meeting the following year was quickly accepted, other offers followed, the term "Midwest" was soon dropped, and the Forum was on its way.

As you know, the Forum exists in health and happiness without officers, dues, bylaws, or formal membership. Thus it is an event, not an organization. It has a steering committee, and an annual business meeting that tends to be short and highly informal. Our hosts have been 26 state and provincial surveys (two of them, Ohio and Indiana, have been repeaters). Hospitality has ranged from Florida to Alberta and from New York to the present long-awaited California. Programs are up to the hosts. A recent development has been to schedule a couple of day-long field trips after the formal sessions. These get us outdoors to look at rocks instead of sitting inside hearing about them.

Besides organizing a meeting, the host agency publishes the resulting papers. This means that over the years our proceedings have appeared as publications of 20-some geological surveys, rather than as a uniform series under our name. An index to the proceedings of the first 25 Forums, 1965-1989, is available, courtesy of our Oregon hosts of 1990. It includes the names and addresses of sponsoring agencies. A few of the early proceedings are out of print, but most remain available.

At the first Forum, in 1965, I stated as follows: "All are acquainted with the standard rock-products flowsheet, which starts at the upper left-hand corner with a truck unloading into the primary crusher beneath the words 'From Quarry.' Communication which is geological has to do with what is to the left of the primary crusher, out there in the quarry." In general, this quarryward orientation has continued over the years.

## INDUSTRIAL MINERALS AND ITS CONGRESSES

Communication in our field may be said to have taken a quantum jump in 1967, with the appearance of the monthly magazine *Industrial Minerals*. At last we had a spokesperson.

Published in London, the magazine is dominantly, though by no means exclusively, a trade journal. Its scope is worldwide. Issues cover selected materials from geology to markets; they also provide up-to-date information on the constantly changing international picture, as companies divide, merge, acquire new properties, or shed old ones. In addition, the magazine gives, at least to this reader, a sense of "belonging" to a vast and seemingly amorphous field of endeavor.

In 1974 the publisher brought together some 400 interested people in London for the first "Industrial Minerals" International Congress. They heard papers on a wide range of topics, from geologic aspects of an undeveloped deposit to the testing of final products, and had opportunity for informal exchange of views and information. Several field trips followed the meeting. Similar congresses have been held, at two-year intervals, in Munich, Paris, Atlanta, Madrid, Toronto, Monte Carlo, Boston, Sydney, and San Francisco. The 1994 Congress will be in Berlin. Attendance at these meetings has exceeded 500 persons, representing as many as 40 countries. Proceedings are published by the sponsoring organization. Notwithstanding travel costs and stiff fees for registration and proceedings volumes, many consultants as well as company and government personnel find it well worthwhile to attend the Congress.

## OTHER COMMUNICATORS

The Ontario concern that publishes *Industrial Specialties News* presents an annual Canadian Conference on Markets for Industrial Minerals. As the title indicates, the subjects considered are mostly market-related rather than geological. The fourth conference met in October 1992.

In past years the publisher of *Industrial Minerals* has sponsored several product-oriented meetings, on such topics as raw materials for glass, refractories, and oil-well drilling.

Starting in 1988, the U.S. Geological Survey and the U.S. Bureau of Mines, in cooperation with the appropriate state surveys, have held annual "workshops" on construction materials and industrial minerals. These have met in Tempe, Marina Del Rey, Salt Lake City, St. Louis, and Minneapolis. Focus has been on planning, land use, and regional resources. It is gratifying to see the august USGS manifesting an interest in such earthy matters.

In 1991 a conference on valuation of industrial-mineral resources was sponsored by the University of Alabama and the Alabama Survey. The next year, a conference on industrial-minerals development in Oklahoma attracted about 125 persons. Also in 1992, agencies in Indiana, Ohio, and Michigan sponsored the Midwest Wetlands Conference in Indianapolis; and the Kentucky Geological Survey was host to a conference on limestone and lime for  $\text{SO}_2$  and pollutant control in the Ohio Valley, attended by some 250 persons. Clearly, recent years have seen an accelerating interest in our field.

## CONCLUSIONS

From this review it is apparent that more of the activity in the field of industrial minerals is in application and markets than in geology. This is fortunate for us, for two reasons. First, the more information on applications and marketing the better the development of demand for our products. Second, the situation leaves the field of geology almost completely to the Forum. (Not to the journal *Economic Geology*, incidentally, which continues to devote 95 percent of its space to papers on metallic ore deposits.) So I conclude in the hope that the Forum will continue to focus on the geologic end of the spectrum. Let us continue the tradition that Larry Rooney once described as "the blend of communication and conviviality that has become the Forum's trademark."







# Biotechnology and Industrial Minerals

by  
Nelson R. Shaffer<sup>1</sup>

## ABSTRACT

Glamorous, burgeoning biotechnology and mundane industrial minerals would at first glance seem to share little in common, but in truth, modern biotechnology depends on many minerals. Biotechnical processes also can be used in industrial mineral extraction and processing. Biotechnology is broadly defined as the application of biological organisms, systems, or processes to manufacturing and service industries. Genetic engineering has reinvigorated one of mankind's oldest sciences, biotechnology, into a booming business. Many modern processes depend on microorganisms cultivated under very stringent conditions in bioreactors. Minerals from carbonate, sulfate, chloride, nitrate, phosphate, and silicate families are used to provide essential nutrients and to regulate growth conditions (such as pH) in order to assure optimal growth of organisms. Certain cells or enzymes perform better when immobilized upon or within solids, and minerals are often used to immobilize cells, especially in continuous process. Minerals are also used extensively in separating and purifying products of biotechnology. Diatomite, zeolites, and silica are especially useful in purification processes. Industrial minerals also are commonly used to clean up large volumes of process water that must be treated.

Biotechnology can be employed in exploration, extraction, and processing of geologic materials and in reducing mining or other environmental problems through bioremediation. Microbes have been shown to solubilize certain elements and so promote extraction of heavy metals, phosphate, aluminum, potassium, and even rare earth elements. In a related technique, unwanted materials such as pyrite impurities can be leached microbially to produce cleaner products in sand and clay industries. Microbial actions can modify surface characteristics and so enhance certain ceramic properties. Certain organisms can accumulate useful elements from dilute sources; others can transform unusable chemical species to more useful forms. Deterioration of stone, concrete, and even glass or brick, can be accelerated by microorganisms. Control of such biodeterioration could improve long-term performance of industrial mineral products. Microbial processes have shown promise in improving several mine-related problems. Certain bacteria help remove clays from phosphate slimes and other suspensions. Others are used to degrade cyanide or other organic chemicals such as floatation aids. Cells immobilized on clays have been especially efficacious in bioremediation.

Biotechnology industries, like the industrial minerals industries, encompass huge ranges of materials and processes. Costs of products from these industries range from pennies to thousands of dollars per unit, and their products are vital for maintaining modern life styles. Many biotechnical processes depend upon industrial minerals and certain biological processes can be harnessed to do useful tasks in the minerals field. The interplay of industrial minerals and biotechnology is important today, and as biotechnology advances, its interaction with the industrial minerals industry can only increase.

## INTRODUCTION

Biotechnology has been heralded by numerous books and articles as nothing less than a scientific revolution with new breakthroughs being reported daily. Almost limitless opportunities exist to produce new materials or techniques using these new discoveries. Biotechnology is broadly defined as any applications of organisms, biological systems, or biological processes to the manufacturing and service industries. This "new" technology is, in fact, one of mankind's oldest and most important scientific activities (Table 1), which has been recently revolution-

ized by the techniques of genetic engineering, biochemistry, and information sciences.

Agriculture, brewing, and chemical and pharmaceutical production are well-known industries that have used biotechnology for centuries. The U.S. Office of Technology Assessment (OTA, 1984, 1992) uses a broad definition of biotechnology that includes any technique using living organisms (or parts) to make or modify products, to improve plants or animals, or to develop microorganisms for specific uses. Current definitions refer to genetic manipulation and the various techniques that are used in industrial applications such as cell culturing, enzymol-

<sup>1</sup>Indiana Geological Survey and Department of Geological Sciences, Indiana University, Bloomington, Indiana 47405

Table 1. Historical development of Biotechnology (from OTA, 1984; Smith, 1988, Ehrlich, 1990; Scragg, 1991; Ralph, 1985b).

before 3000 BC	Proofing bread with leaven
before 3000 BC	Fermentation of juices to alcoholic beverages
before 3000 BC	Knowledge of vinegar formation from fermented juices
about 150 BC	Copper recovery from China
from 1150 AD	Production of spirits of wine (ethanol)
before 1670	Copper mined at Rio Tinto, Spain
1881	Microbiological production of lactic acid
1888	Winogradsky observed bioaccumulation of iron
1890	Bacterial role in rock weathering by Muentz
from 19th century	First communal sewage plants in Berlin, other cities
1928/1929	Discovery of penicillin by Fleming
1937	Microbiological transformations discovered by Mamoli and Vercellone
1941/1944	Beginning of penicillin manufacture
1944	Discovery of streptomycin by Schatz and Waksman
1947	Colmer and Hinkle show microbial oxidation
from 1950	Discovery of many other antibiotics
1950s	ZoBell's work with sulfate-reducing bacteria and petroleum microbiology
1953	Discovery of the structure of deoxyribonucleic acid by Watson and Crick
1962	Microbial uranium mining in Canada
Modern Era	
1973	First cloning of a gene
1973	Brazilian alcohol fuel program
1975	First hybridoma created
1976	First US firm to exploit rDNA technology
1980	Supreme court rules that micro-organisms can be patented
1981	First monoclonal antibody diagnostic kits
	First automated gene synthesizer marketed
1982	First rDNA pharmaceutical product (human insulin) approved
1983	First expression of a plant gene in a plant of a different species
1985	Permit issued by EPA for release of a genetically altered organism
1986	Technology Transfer Act of 1986 rights to commercialize government research
1988	NIH establishes program to map the human genome
	First US patent on an animal—transgenic mouse
1989	Bioremediation gains attention
1990	FDA approves recombinant renin, an enzyme used to produce cheese
	First approval of human gene therapy clinical trial
1991	Biotechnology companies sell \$17.7 billion in new stock
	EPA approves the first genetically engineered biopesticide for sale
1992	Transgenic food approved
	Gene therapy trials

ogy, separation, and purification. In other words, biotechnology is the manipulation of living organisms and/or biological processes to provide useful products. The "new" biotechnology would further narrow the definition to processes using genetically engineered microorganisms, cells, or enzymes.

Industrial minerals play critical roles in biotechnology, and in turn biotechnology holds real potential to improve extraction, beneficiation, and performance of industrial minerals themselves. Agriculture and food processing, the oldest forms of biotechnology, entail use of numerous industrial minerals as fertilizers, soil condi-

tioners, or animal feeds. Many chemicals are prepared by biotechnological processes, and since the 1940s, fermentation technology has been instrumental in producing medicines such as penicillin. Several industrial minerals are used directly as fillers for pharmaceuticals. Clays, carbonates, zeolites, and other minerals are used as carriers or fillers in medicinal compounds (The United States Pharmacopeia, 1990). Gypsum used in dental casts, mercury in amalgam, and dental porcelain in crowns are important to dentistry. Alumina, zirconia, apatites, and bioactive glasses have seen service as implant materials (Williams, 1990).

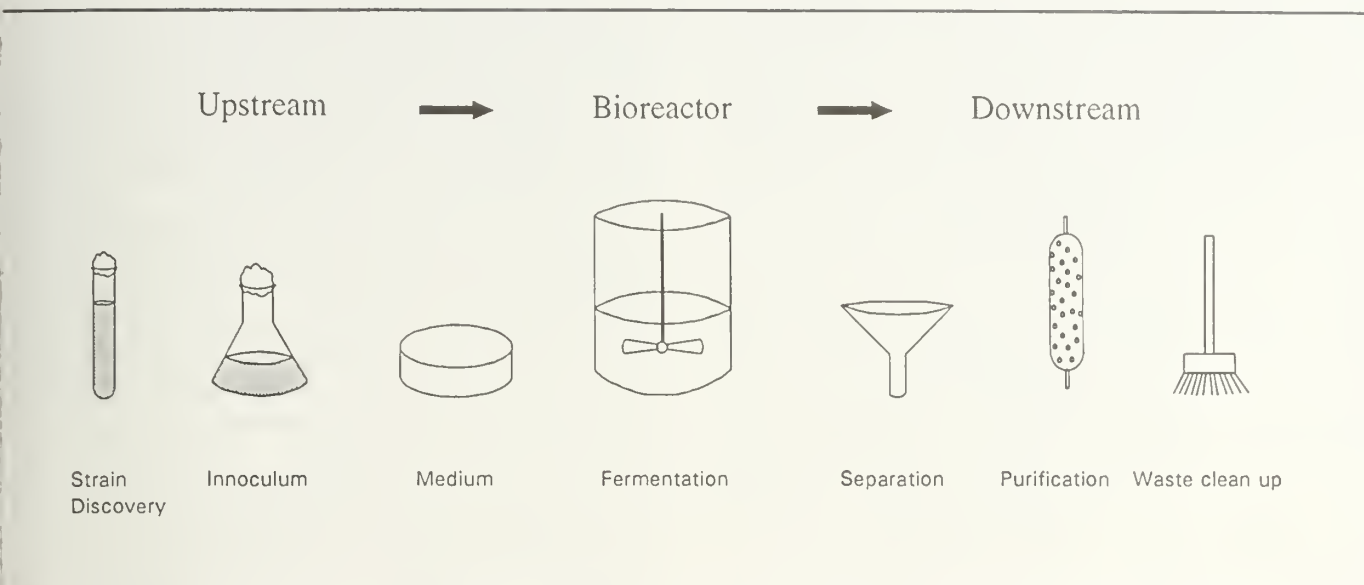


Figure 1—Generalized flow diagram of fermentation processes

Fifteen established firms as well as 300 small, growing companies are involved in the creation of engineered organisms. Revenues exceeded \$2 billion in 1990 and are expected to grow to \$50 billion by the year 2000 (OTA, 1992; Burill and Roberts, 1992). The United States is currently the world leader in biotechnology but Japan, the UK, Switzerland, France, and other countries have large, well-funded national programs in biotechnology. Most successful industry efforts have focused on high-value products, but efforts to produce or transform industrially important chemicals are also underway (Ng et al., 1983; Thayer, 1991; Hinman, 1991), and considerable research into environmental and geologic uses of biotechnology has begun.

Microbial mining (Ehrlich and Brierley, 1990), enhanced oil recovery (Donaldson et al., 1989), coal desulfurization, bioremediation, and other geologic aspects of biotechnology are covered extensively elsewhere; the interaction between biotechnology and industrial minerals will be investigated here. Also discussed will be uses of biotechnology to discover, recover, and beneficiate industrial minerals. Because most industrial minerals geologists are unlikely to be acquainted with biotechnology, a brief overview of the discipline will be presented.

## THE BIOTECHNOLOGY BUSINESS

Actual production in biotechnology usually depends on controlled fermentation, which can be defined as any process that produces a useful product by mass culture of microorganisms (Walker and Cox, 1988). The general flow diagram of a biotechnical process (Figure 1) shows that fermentation is serviced upstream by provision bacteria, preparation of growth media, and sterilization.

Very well characterized microbes are added to the media and allowed to grow. Useful products are harvested and then purified to final products by various downstream separation processes.

Fermentation is carried out in fermenters or bioreactors (Figure 2), which are fully sterilizable vessels in which organisms can be grown to produce cell mass or products such as enzymes or metabolites, or to transform compounds added to the reactor. Bioreactors are usually cylindrical stainless steel tanks that range in size from a few liters up to about 500,000 liters. Fermenters can operate in a batch or continuous mode (Crueger and Crueger, 1990; Stanbury and Whitaker, 1984). Batch fermenters operate by loading the reactor, sterilizing it, adding microbes, running reactions, removing broth, and cleaning the reactor. This method is analogous to brickmaking by periodic kilns. In continuous fermentation, sterile media and microorganisms are added continuously as processed media and product are removed analogous to tunnel kiln operation. Some processes work better with fixed-bed reactors in which microbes are immobilized on some solid substrate. Reactors are closely monitored so that growth can be optimized. They are fed by numerous pipes that bring air, raw materials, pH control agents, and other process aids; other pipes remove byproduct gases, and product. Microbial growth produces heat, which is usually dissipated by a cooling jacket. Most commercial microbes need air and so most reactors are stirred to provide microbes access to nutrients and sterilized air.

Many waste-water bioreactors are not operated under sterile conditions but most other fermentations do require sterile reactors, components, and air. Air can be



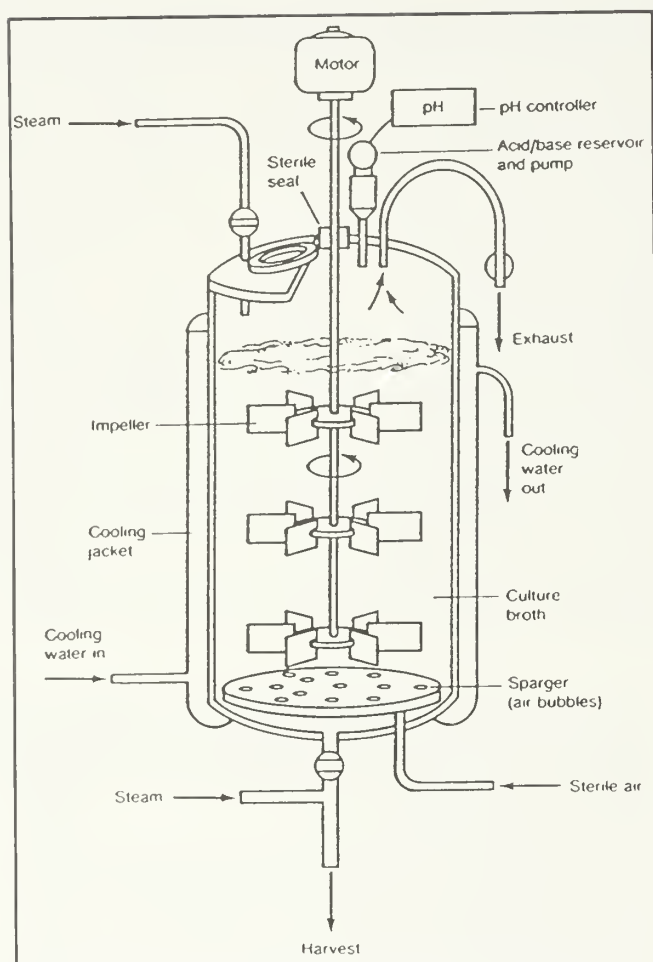


Figure 2. Schematic diagram of generic large-scale, stirred bio-reactor or fermenter (from Brock and Makigan, 1991).

sterilized by heating, irradiation, chemicals, scrubbing, or filtration, but only heat and filtration are practical at industrial scales. In the past, activated carbon, mineral wool, or asbestos were common filter material, but now glass-fiber filters and cartridges are the most commonly used sterilization items (Crueger and Crueger, 1990).

All organisms require certain essential elements to live and grow; one of the major uses for industrial minerals is in making growth medium. Organisms are grown in specifically formulated culture media to optimize cell growth or production of desired product. Major required elements are C, N, P, H, and O. Na, K, Ca, Mg, S, and Cl make up the remainder of the essential elements. An additional 17 trace elements occur more sporadically and in very low amounts (Frausto-DeSilva and Williams, 1991). Mineral components can account for 4 to 14 percent of the cost of biotechnical production. Considerable amounts of industrial minerals are consumed directly as animal food (Allen, 1992) and plant food (Kilmer, 1979) in conventional agriculture and additional amounts are needed to grow microorganisms in biotechnology. Tables 2A and B list industrial minerals used in this step as well as those used in other aspects of fermentation.

Industrial minerals also help control the fermentation process. Calcite can be used as a buffer or pH control, as can mineral acids. Certain materials seem to aid cell growth and are used even though their exact functions are unknown. Examples of these are calcite, clay, or vermiculite. Sikyta et al. (1983) and Smith et al. (1980) both noted that carbonates from different sources showed very different effects on growth. Recently Sreekumar and

Table 2A—Inorganic compounds and minerals used in making culture media for biotechnology

$\text{KH}_2\text{PO}_4$	$\text{NH}_4\text{NO}_3$	$\text{CaSO}_4$	$\text{MgSO}_4^*$	$\text{NaCl}$	$\text{KCl}$
$\text{K}_2\text{HPO}_4$	$\text{KNO}_3$	$\text{FeSO}_4^*$	$\text{ZnSO}_4^*$	$\text{CaCl}_2^*$	$\text{FeCl}_3$
$\text{Na}_2\text{HPO}_4$	$\text{NaNO}_3$	$\text{MnSO}_4^*$	$\text{CuSO}_4^*$	$\text{MgCl}_2$	$\text{MnCl}_2$
$\text{Na}_3\text{PO}_4$	$\text{Ca}(\text{NO}_3)_2$	$\text{K}_2\text{SO}_4$	$\text{CoSO}_4$	$\text{NH}_4\text{Cl}$	$\text{ZnCl}_2$
$\text{CaHPO}_4$	$\text{Na}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$	$\text{VSO}_4^*$	$\text{Al}_2\text{SO}_4^*$	$\text{SrCl}_2 \cdot 6\text{H}_2\text{O}$	$\text{CuCl}_2 \cdot 2\text{H}_2\text{O}$
$\text{NaBr}$	$\text{KI}$	$\text{Na}_2\text{SO}_4^*$	$\text{NH}_4\text{SO}_4$	$\text{NiCl}_2 \cdot 6\text{H}_2\text{O}$	$\text{CoCl}_2 \cdot 6\text{H}_2\text{O}$
$\text{NaF}$	$\text{Na}_2\text{B}_4\text{O}_7 \cdot 10\text{H}_2\text{O}$	$\text{NaMoO}_4 \cdot 7\text{H}_2\text{O}$	$\text{NaHSO}_3$	$\text{HCl}$	$\text{H}_2\text{SO}_4$
$\text{Na}_2\text{S} \cdot 9\text{H}_2\text{O}$	$\text{HBO}_3$	$\text{H}_3\text{PO}_4$	$\text{NaOH}$	$\text{LiCl}$	$\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$
$\text{CaCO}_3$	$\text{NaHCO}_3$	$\text{Na}_2\text{CO}_3$	$\text{NaKCO}_3$	$\text{K}_2\text{CO}_3$	$\text{AlCO}_3 \cdot 6\text{H}_2\text{O}$
$\text{H}_3\text{PO}_4$	$\text{KOH}$	$\text{SnCl}_2$	$\text{NiSO}_4 \cdot 6\text{H}_2\text{O}$		

Table 2B—Inorganic compounds and minerals used as process aids

pH Control	Sterilization	Growth Aids
Phosphoric Acid	Glass Fiber	Clays - Unspecified
Sulfuric Acid	Mineral Wool	Vermiculite
Boric Acid	Asbestos	Limestone
Calcite	Norite	Gypsum
Sodium Hydroxide		
Potassium Hydroxide		

\*Plus variously hydrated compounds

Sources: Crueger and Crueger, 1990; Gherna and Pienta, 1992; Stanbury and Whitaker, 1984; Atkinson and Mavituna, 1983.



Basappa (1992) reported that addition of carbonate or  $\text{CaCl}_2$  improved ethanol production but that  $\text{NaCl}$  additions decreased output. Klausmeier et al. (1963) demonstrated 3- to 10-fold changes in fungus development by varying kinds and amounts of mineral salts. Many metals (Hughes and Poole, 1989) show toxic effects on microbes.

Clay minerals influence microbial growth in soils so it is not surprising that clays show considerable effects in media; Weaver and Dugan (1972) reported increased bacterial methane oxidation when clay particles were present and polysaccharide production was enhanced by clay additives (Lanza and Watson, 1984), but growth was decreased by adding kaolinite (Maigetter and Pfister, 1975). Perez-Rodriguez et al. (1989a, b) reported effects of several clays in anaerobic bioreactors, with treated sepiolite enhancing good methanogenic bacteria while repressing sulfate reducers. More studies about clay mineral reactions with bacteria under geologic or industrial conditions need to be done.

Clays interact readily with organic compounds and so make good carriers for pesticides. Numerous studies of clay/pesticide/organism interactions appear in the literature (Boudot, 1992; Öya et al., 1991; Stockmeyer, 1991). Bacteria (Daniels, 1972) and viruses (Lipson and Stotzky (1984) adhere to inorganic particles and can thereby grow more vigorously. One school, as championed by Cairns-Smith (1982) and Cairns-Smith and Hartman (1986), suggests that life arose by reaction of clays and prebiotic organic compounds.

Certain cells grow better when attached to solid supports. Daniels (1972), Kolot (1981a, b), and Kovalenko and Sokolovskii (1992) list more than 40 inorganic compounds (Table 3) known to adsorb microorganisms onto their surfaces. This property allows immobilizing cells or enzymes onto inorganic supports thus improving production by increasing cell density, prolonging cell life, protecting cells from shear stresses or high pressures, providing mechanical stability, and allowing easier recovery of cells or enzymes. Immobilized materials acting as biocatalysts can increase reaction rates by  $10^3$  to  $10^{11}$  times over noncatalyzed rates. Immobilization is such an important topic it constitutes a multi-billion-dollar industry (Klibanov, 1983), and books have been written specifically about it (Chibata and Wingard, 1983; Tampion and Tampion, 1987; Hartmeier, 1988).

Treated glass beads, ceramics, diatomite (Anderson et al., 1990), magnetite, or even sand (Bon, 1984) are used to physically entrap cells into microcarriers. Ceramics are also used as monolithic supports for continuous culture (Shiraishi et al., 1989; Lydersen et al., 1985). Much remains to be learned about industrial minerals and immobilization.

After fermentation is completed, the broth with cells, spent media, and product must be separated through downstream processes to yield a pure product. Efficient handling is critical as 20 - 60 percent of total manufacturing costs are made up of by product recovery (Stanbury and Whitaker, 1984). Several industrial minerals play roles in separation and purification (Table 4). Most

notable are clays and diatomite that are used extensively as filter aids; chlorides and sulfates that act as flocculants or crystallization aids; and zeolites, clays, silica, and other materials that are used in several purification steps.

If desired products are held inside the cells they must be disrupted. Heating, detergents, osmotic shock, or grinding with glass abrasive materials are sometimes used to help disintegrate cells and solids separated from the broth by filtration or centrifuge. Large quantities of diatomite are used to aid in certain kinds of filtration. Alum, calcium, ferric salts, bentonite (Gasner and Wang, 1970), and organics (Purchas, 1968), are useful in improving flocculation and thus enhancing efficiency of centrifugation. Products concentrated by precipitation or crystallization can be enhanced by in-

Table 3—Inorganic supports for immobilizing cells or enzymes

Alumina	Clay	Montmorillonite
Alumina (soil)	Coal	Nickel Oxide
Aluminum Hydroxide	Coke	Pumice
Aluminum Phosphate	Diatomite (cellite)	Pyrite
Anthracite	Diatomaceous Earth	Pyroxene
Antimony Pentasulfate	(Kieselguhr)	Quartz
Asbestos	Emery	Sand
Ash	Ferric Hydroxide	Sepiolite
Attapulgeite	Ferric Oxide	Silica
Ball Clay	Fullers Earth	Silica Gel
Barium Sulfate	Glass	Stainless Steel
Bentonite	Graphite	Sodium Aluminum Silicate
Bentonite Acid	Halloysite	Sulfur
Bentonite Amine	Hornblende	Talc
Brick	Hydroxyapatite	Titania
Calcium Carbonate	Illite	Vermiculite
Calcium Oxalate	Kaolinite	Volcanic Rock (Kisiris)
Calcium Phosphate	Lava	Zeolites
Ceramics	Magnesium Hydroxide	Zinc Hydroxide
Charcoal	Magnesium Oxide	Zirconia
Cinnabar	Magnesium Pyrophosphate	Zirconium-Earth
Cordierite	Manganese Oxide	Unspecified rocks, ores, etc.
	Meerschaum	

Table 4—Techniques of downstream processing and some materials used for separation and purification.

Techniques			
Disruption	Separation	Concentration	Purification
Osmotic Shock	Flocculation	Adsorption	Crystallization
Heat/Cold	Flotation	Membrane Filtration	Ultrafiltration
Detergents	Filtration	Precipitation	Chromatography
Chemical Lysis	Precipitation	Solubilization	adsorption, gel
Abrasion	Centrifugation	Solvent Extraction	affinity, ion exchange
Materials Used			
Halite	Iron Salts	Alumina	Apatite
Glass	Calcium Salts	Clays	Coal
Alkalis	Sodium Silicate	Zeolites	Clays
	Alum	Silica	Silica
	Diatomite	Greensands	Zeolites
	Clays	Activated Charcoal	Diatomite
			Zr Compounds

Sources: Asenjo, 1990; Crueger and Crueger, 1990; Atkinson and Mavituna, 1983; Standbury and Whitaker, 1984; Dechow, 1989.

dustrial minerals such as  $\text{NH}_4\text{SO}_4$ ,  $\text{NaCl}$ ,  $\text{NaSO}_4$  (Wiseman, 1983),  $\text{NaF}$ ,  $\text{CaSO}_4$ , or  $\text{BaCO}_3$  (Donaldson, 1984), or  $\text{Ca}(\text{OH})_2$  in processes generally known as “salting out.”

Purification of the finished product is usually necessary after initial filtration and separation. Inorganic absorbants such as aluminum oxide, aluminum hydroxide, magnesium oxide, silica gel, and active carbon as well as a range of diatomite (celite), bentonite, glass, alumina salts, calcium phosphate, barium sulfate, rutile, and organic resins are used in adsorption chromatography (Atkinson and Mavituna, 1983; Miles and Thompson, 1974). Bentonite is especially well known for purifying alcoholic beverages. Activated carbon, clays, silica gel, and zeolites are also useful in biochemical processing (Blum and Eriksson, 1991; Cheng and Lee, 1992), which also are used in filtering gas and water.

In summary, many industrial minerals play roles in biotechnological production. Even though it is not possible to determine exact amounts used in biotechnology, usage of certain materials is substantial and use can only increase as the industry grows and as cost considerations dictate use of the most efficient raw materials. Published research about mineral properties (especially at very fine scale) and their relationships to biotechnologic requirements is slight; better understanding of mineral-bacteria interactions will provide new avenues of production and improved economics.

## BIOTECHNOLOGY AND GEOLOGY

Geomicrobiology investigates interactions of microbial life and geologic materials and processes. Microorganisms are the earliest recognized life forms and they efficiently perform every conceivable (and probably many as yet undiscovered) low-temperature chemical reaction. Perlman (1980) said, “Microbes can and will do anything: microbes are smarter, wiser, and more energetic than microbiologists, chemists, engineers, and others.” Overviews of geomicrobiology are provided by Ehrlich (1990), Zajic (1969), and Krumbein (1983). Ralph (1985a, b) related geomicrobiology to the new biotechnology with special emphasis on microbial leaching.

Microorganisms' potential to recover minerals was recognized early (Brierley, 1978) and has since been studied extensively, resulting in a vast literature about microbial leaching or mining reviewed recently by Ehrlich and Brierley (1990), Attia (1990a), Ehrlich and Holmes (1986), Scheiner et al. (1989), Murr and Brierley (1978), and Schwartz (1977). Others have speculated on new uses for biotechnology in mining or processing (Nicolaidis, 1987; Smith et al., 1991; Borman, 1991, and in various Proceedings of the International Biohydrometallurgy Symposium). Commercial biorecovery of copper, uranium, and gold is in operation (Hutchins et al., 1988; Salley et al., 1989).



Organisms used in metal-leaching also can remove sulfur from coal. Biological methods of coal desulfurization hold promise of removing intractable organic sulfur components. Scheiner et al. (1989), Attia (1990b), Kargi (1986), Kilbane (1989), and Andrews and Maczuga (1984) are but a few of the many papers about microbial coal desulfurization. Certain organisms even help to solubilize coal (Faison, 1991), and in situ biological conversion or desulfurization of coal may someday be feasible, (Jutgen, 1987).

Microbial-enhanced oil recovery, known as MEOR, has been studied (Updegraff, 1990; Yen, 1990; Bryant, 1989; Donaldson et al., 1989; Zajic et al., 1983). Microorganisms produce gases or surfactants that increase pressure in the reservoir, reduce oil viscosity, and improve mobility. Bacteria can even promote porosity by acid production that dissolves carbonate rock. Microbes can also affect nonpetroleum organic matter. Oil shales and sands contain immense reserves that are not extractable by conventional techniques. One of the most probable uses in geologic realms for the new biotechnology is the development of organisms that can economically modify kerogen or asphalt into fluids that can be produced, transported, and processed like common petroleum. Papers about microbial oil recovery from oil shales or the interaction of microorganisms and oil shale include Yen (1976, 1977), Scott and Irish (1988), and Jones (1990).

## BIOTECHNOLOGY AND INDUSTRIAL MINERALS

Most geologic research has focused on biological leaching of sulfide or other ores, but several papers including Ralph (1985a) and Groudev (1987), have shown the efficacy of microbial techniques in mining or in beneficiation of industrial minerals. Major microbial processes of solubilization, accumulation, surface changes, or biotransformations have been applied, and many other untried possibilities exist. No genetic engineering experiments for industrial minerals applications have been reported as yet.

Microbes often accelerate dissolution of minerals. Solubilizing phosphate from ore has been reported (Rogers et al., 1989) as part of an extensive program at the Idaho Falls National Laboratories. Groudev and Groudev (1986a) reported leaching of aluminum and Rossi (1978) extracted potassium from leucite using bioleaching. Glombitza et al. (1988) succeeded in microbiologically leaching rare earth elements from zircon. Rossi and Ehrlich (1990) and Ralph (1985a) reviewed microbial leaching of nonmetallic materials; many other minerals could be solubilized thus allowing inexpensive extraction of many industrial minerals by using biotechnological techniques.

The opposite approach - reverse solution - solubilizes and removes unwanted contaminants from the desired minerals. Groudev and Groudev (1985, 1986b) removed iron from quartz sand using microbial reverse leaching. They also removed iron from clays, and improved kaolin and clay ceramic properties via microbial action (Groudev et al., 1989, 1991). Groudev and Groudev (1988a, 1988b) reduced silica content in fine bauxite ores by microbial leaching as did Karavaiko et al. (1989). Mohanty and Mishra (1989) reported microbial silica removal from magnesite ore.

Another useful microbial technique is absorption of elements from waste or other waters. Elements, such as strontium (Faison et al., 1990), germanium (Chmielowski and Klapcinska, 1986), actinides, and even radioactive elements, have been absorbed by microbial means (Macaskic, 1991). Microbial absorption is covered by Ehrlich and Brierley (1990) and the U.S. Bureau of Mines has an active program of biosorption research. As in the case of microbiological leaching, most efforts have been directed toward metal absorption (Volesky, 1990; Hughes and Poole, 1989; Beveridge and Doyle, 1989).

Microbes can alter mineral surfaces and so lead to different or enhanced properties. Groudev et al. (1989, 1991) demonstrated improved kaolin properties such as strength, plasticity, shrinkage, and absorption after microbial treatment. Bacteria also affect surfaces of biotite, pyrite, and many other minerals (Boyle et al., 1967; Attia, 1990b). Carbonate minerals could be treated to increase surface area and improve brightness for paper, or increase reactivity for SO<sub>2</sub> scrubbing. Modifications of flotation properties have also been demonstrated, and it may be possible to enhance or suppress flotation of a particular mineral by treating it microbially.

Microorganisms are important in decay of natural stone and in soil formation (Berthelin, 1983; Krumbein and Dyer, 1985), whereby they produce the marvelous mantle of soil that makes possible all life. However, they also cause unwanted decay in man-made materials, thus an entire field - biodeterioration - studies and ameliorates effects of biological degradation. A recent bibliography lists more than 600 articles on stone biodeterioration (Koestler and Vedral, 1991). *International Biodeterioration* and a series of international symposia also cover aspects of stone decay. Special attention has been paid to biodeterioration of ancient stone statues and buildings and to ways of combating decay (Felix, 1985). Krumbein (1987), Jones and Wilson (1985), and Strzelczyk (1981) give reviews of the overall problem.

Sandstone, concrete, plaster, and other building materials are also affected by bacteria (Hueck-van der Plas, 1968). Even granite, brick, ceramics, and glass are subject to biodeterioration (Krumbein et al., 1991). Most

exposed materials are subject to microbial attack, but surprisingly little research is reported about suppressing microbial growth and deterioration. Grant and Bravery (1981) evaluated several materials for destruction of algae on construction materials. Griffin et al. (1991), Schnabel (1991), and Richardson (1987), reported techniques for controlling microorganisms on stone. Physical methods of stone cleaning as well as biocide treatment must be repeated and, therefore, are no panacea. There remains to be found a long-term solution to the problems of biodeterioration by microorganisms. The tendency of bacteria to degrade materials can, however, be turned to good use.

Bioremediation is a term for modern microbial methods of removing harmful pollutants or modifying them to be less harmful. More than 250 future projects are being evaluated (Swett, 1992). Most often bioremediation is used to transform organic contaminants into less noxious substances (Mitchell, 1992; Thayer, 1991b), but several biotechnical techniques show promise in cleaning mining wastes even though this application is still in its infancy.

Microbial processes show promise for removing clay from phosphate mining wastes (Brierley et al., 1981; Leslie et al., 1984) or other suspensions (Avnimelech et al., 1982). Bacteria degrade cyanide used in metal extraction and Carta et al. (1980) suggested biochemical beneficiation of effluents from nonmetallic flotation plants. Omar and Rehm (1988) showed that organisms immobilized on granular clay pellets degraded oily sludge twice as fast as free cells. In situ bioremediation is affected by soil clays (Miller and Alexander, 1991; Boudot, 1992) and considerable work on clay-organism interaction remains to be done. Diatomaceous earth has proved useful in removing viruses from water (Farrah et al., 1991). There are undoubtedly many other areas where biotechnology can be used to improve mining beneficiation, and reclamation.

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# Intravenous Geology

by  
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## ABSTRACT

A few years ago during a Southeastern Geological Society field trip, a professor from a Florida university and a trip leader commented at one of the stops, "... and for those of you interested in the geology..." More recently, in the spring of 1992, a geology faculty member at another southeastern university remarked, "Field geology is obsolete." An interviewee for a potential assistant position stated that he had never had a field class. This would-be assistant was to receive his Master's Degree in Geology within a few days from yet another southeastern university. A regional illness? Certainly not, but symptomatic of the general health of Geology.

Capitulation to Environmental Sciences seems to be in vogue with Geology becoming a four-letter word and the mention of mining is verboten regardless of the company.

These trends permeate our profession while the demands for earth materials increase, often exponentially. Efficiency, a word lost on government, is routinely expected of business--our business--the industrial minerals geologist and producer. Our stage shrinks but the responsibilities expand. Are we meeting the challenge? Stay tuned!

## INTRODUCTION

The monthly publication of the American Institute of Professional Geologists is titled *The Professional Geologist*. As I began to "set down" my thoughts for this presentation, the back cover of the February, 1993 issue of that publication caught my eye and had that heading been noticed earlier, it may very well have become the title of this talk. The heading was, "Show Your Pride!" I'm afraid that for various reasons, we are all guilty of not having shown our pride as geologists. Perhaps a combination of the front and back cover--*The Professional Geologist*, "Show Your Pride"--should become our slogan in these times of mining-bashing.

Perhaps a good dose of introspection is in order and long overdue. Are we, as living, breathing individuals, professional geologists? Do we take pride in our profession and equally important, do we "show pride" in our profession? Do we spend more time complaining about engineers, surveyors and other would-be pseudo-geologists encroaching upon our territory than we do in positive promotion of our profession? Also, and as presently occurring, are we not continuing to preach to the choir rather than becoming involved in political and civic activities/endeavors where our energies may well better benefit our profession? Does the "closet scientist" description actually portray us as a group? Do educators (?) or geology programs purposely avoid our own four letter word "mine" in favor of "environmental inter-disciplinary sciences?" Are the organizations to which we all belong

also guilty of similar cowardice? These are but a few of the questions we could pose to the mirror with embarrassing responses.

In 1991 I listened to a panel discussion as rather distinguished geologists gave their versions of professionalism. One panel member did not see a relationship between professionalism and moral character. Maybe he was legally correct, but thankfully, his definition was only an opinion rather than a statute. Personally, such a statement was repugnant to me and to another panel member who voiced his objection in clearly understandable terms and recognizable colloquiums. Non-accountable conduct has become acceptable in too many high places at the expense of national morality and professional integrity. Are we professionals or are we "bottom line" participants with short term outlooks.

There are those of you here in the audience this morning who told me--regarding attendance at geologic meetings--"If the company doesn't pay for it, I'm not going." Ladies and gentlemen, as much as it may pain me to say it, or for you to accept, generally your company doesn't give a \_\_\_\_ [expletive deleted] about your professional development or the development of your profession! (sic) This is an unsubsidized pursuit.

So where do we begin? To me, we begin by substituting oral affirmations rather than "intravenous geology" and with an emphasis on the "we." By intravenous geology, I mean that we as professionals intimately know the critical importance of geology and the vital necessity

that minerals provide to our quality of life; the significance of which is far too often left unspoken.

Perhaps, just as the dashboards of our cars have gone symbolic, a graphic touting of our profession is also in order. Please bear in mind as a consistent underlying theme to my remarks, that there is no personal egotism involved here, rather the thrust is toward respect and acceptance of geology and its place, rather than an egotistical boost for geologists! I should not like to be another "Nattering of Negativism" and have, in all fairness, begun to see some very positive signs, particularly in the grade school curricula programs. Marilyn J. Suiter, in the January 1993 issue of *Geotimes*, notes:

Several science-education reports of the 1980s and 1990s focus on the discrete nature of the training segments of our science engineering and technology pipeline. For example, weather and soil are major science topics at the elementary-school level, but there is minimal coherent focus on earth science in the pre-kindergarten through sixth-grade curricula. And, although earth science is regularly taught at the middle-school/junior-high school level, earth science as an analytical laboratory science hardly exists in high-school curriculum. Throughout the curriculum, the presentation of the variety of career opportunities is minimal.

In recent years, career opportunities in the earth sciences have shifted dramatically. Yet natural resources are still a key commodity of our society, and the exploration and feasible use of those resources will inevitably increase. Similarly, the projection and rehabilitation of Earth environments is a growing area of speculation and legislation, and will require more suitably prepared individuals to study and make recommendations on issues that directly affect the quality of our lives.

In that same issue of *Geotimes*, the article, "USGS Supports K-12 Education," by Laure G. Wallace, describes a number of educational programs, although mining and minerals are never mentioned. Of concern to me, individually, is that the thrust of these and other programs seem to concern themselves more with educational systems and methodology than with actual scientific substance. The following statement illustrates this point: "Designed for the Apple Macintosh® computer, GeoMedia offers students exciting new possibilities for navigating through multiple layers of information."

A bit of pragmatism and reality is found in the *Geotimes* article by Michael J. Baranovic who says: "Of course, modeling can never completely replace the drill bit as the ultimate test of our ideas, but it should provide a means to sharpen our thinking and enhance our creativity." That type of remark gives us antiquated "field geologists" a measure of job security.

In recent years, I was asked to make a presentation during the industrial minerals segment of a Geological Society of America (GSA) sectional meeting. The crux of my remarks that day was a plea to the academic community (a very large segment of the GSA membership) to become more involved in the day-to-day problems confronting the minerals industry and the geologists, mining engineers, et al who serve that industry--pragmatic geology, if you will.

Perhaps that suggestion was selfish on my part. Another, though successfully veiled, purpose was to do my part in breaching the chasm between industry and academia. My paper, along with others presented during that session, was to be published by the host state geological survey. After making all changes and modifications to conform with GSA publication policies as requested by the editorial review board, I was informed that my paper would not be published because it was "not technically interesting" with other papers presented during the session. It was not meant to be! However, by refusing to publish my paper, GSA had actually reinforced the primary point I was trying to make. Is GSA ashamed or embarrassed by those geologists who work with the mining industry, or could my non-member status have been the death knell?

I, like many of you in attendance, have been all around the environmental merry-go-round. It angers me (to say less would be dishonest) to hear the weekend Hollywood type environment espousers bad mouth geologists and mining. The average one of those do-gooders has spent less time purposely involved in environmental pursuits and recognition than I have accidentally. Yet our proclamations have been via intravenous geology, supplying the materials or playing a large part in that supply...with our mouths shut.

The abstract-mentioned field trip incident did not go uncontested. It was pointed out to a professor in charge at one of several quarry stops that the opportunity to study the section and consequent stratigraphic discussions, was in fact provided by the commercial quarrying activity. While paleontology was academically (and indirectly economically) important, the utilization of the material being quarried was commensurately important, and that I believed his entourage of students should be so informed. Needless to say, my suggestion fell on deaf ears. Not vindictively so, but it was my last field trip I attended that was sponsored by that organization. There were other mitigating factors causing a serious negative concern about this event which prompted a letter of concern, not anger, to the organization president. As of the April 1993 Industrial Minerals Forum, I have not received an answer (my letter was mailed 9/22/92), but that organization administrator claims to be a professional geologist. Professionalism?



The "field geology is obsolete" remark was by a professor whose employer department has been under siege to the degree that the abolishment of the Degree in Geology has been considered. Certainly, I do not, nor should anyone, have problems with advances in educational techniques or methodology. However, we should all be alarmed when the techniques or methods become more exciting or the recipient of more interest than the science itself.

Donald C. Haney's "Wake Up Geologists" remarks in the February, 1993 issue of *Geotimes*, bear reading and re-reading by geologists everywhere . . . and then I hope, spurs commensurate action. I had chosen the theme of my tirade for today before seeing Haney's article, but I believe we may have been feeding at the same trough. I am truly pleased that he enjoys a wider audience and hope that both/either of us may spark some reaction. Having obtained Don's permission, I should like to incorporate, at a minimum, these passages:

...Society is rapidly changing in a way that affects our lives as never before. These changes influence how we find, develop, and use our mineral and water resources, how we educate our youth, and even how we use our leisure time. I am convinced that the profession of geology is not responding adequately to these changes.

The long-term strength of a nation is directly related to how it develops and manages mineral resources that drive industry and therefore determine standards of living. The United States is the only major power that has not nationalized its mineral resources."

The role of the geologist is rapidly changing in today's world, and will continue to change into the 21st century. Will we adapt our way of doing things to meet the challenge of the future and make the kind of contribution to society that we should? Or will we continue as usual and complain about the progress of others? We must change. We must address the present and future needs of our nation and the world. We must wake up, geologists!

Walter Schmidt hammers around the need for geologic visibility to the public in the December, 1992 issue of *The Professional Geologist*. Walt says:

...Geologists have been associated with land exploitation and extraction of nonrenewable resources, all generic activities that are not now considered environmentally sound or politically correct.

This is the message we as geologists must get across to the public. Geologists are a major part of the solution to environmental problems caused by our society's appetite for natural resources, not part of the cause!

Perhaps Walt's comments are a bit intravenous, but he works for a state geological survey, and job security and consulting type independence do not always form a symbiotic relationship.

Bill Cutcliffe's guest editorial in the same issue of *The Professional Geologist* discusses the 1990s markets for geologists. He notes (typically for Bill, and not derogatorily), the "changing" markets for geologists and wonders "aloud" for the future. His company embraces many fields, of which industrial minerals may have become a minor part. Nevertheless, Bill sounds a familiar cry for the American Institute of Petroleum Geologists (AIPG) which also, more broadly, applies to our profession as a whole to: "either lead, follow, or get out of the way."

Let's lead, the other two choices are completely unacceptable to "Professional Geologists."

Gilbert M. Grosvenor, Chairman and President of the National Geographic Society, says in the April, 1993 issue of *Sky Magazine*:

Quite simply, geography has been poorly taught for a long time. For too long, it was perceived to be a dull discipline of memorizing state capitals. Meanwhile, our kids are visual, and are so tuned in to moving visual images that you are not going to sit down the way we did 50 or 75 years ago and get them to memorize dull facts.

You have to bring the subject to life. Geography should be the most exciting subject kids study in school. 'The world and all that's in it' - what could be more exciting? But we haven't taught it very well, so our mission is to reach the teachers, empower teachers, improve their skills in teaching geography.

Although never advocating anything approaching plagiarism, isn't "The world and all that's in it," applicable to geology also? For you Delta flyers, Mr. Grosvenor goes on to say later in the article that the first issue of *Sky Magazine* (October 1888) carried an article entitled, "Geographic Methods in Geologic Investigation." (Surprised me too; I didn't subscribe until a few years later.) And finally, from Mr. Grosvenor, "I am absolutely committed to the theory that evolutionary changes are essential and revolutionary changes are often fatal...."

It may seem to many of you that I should have simply submitted a Bibliography of suggested reading, but similar to Hollywood environmentalists, my beliefs become creditable when espoused by better known or more learned people. This next paragraph from Frank Borman's autobiography, "Countdown" is no exception. He says, in reply to a Students for Democratic Society query:

"Look," I insisted, "our society with all its faults has produced the greatest amount of freedom for individuals and the greatest amount of material wealth of

any nation in the world. I don't deny its faults but I don't forget its virtues, as you seem to be doing. How can it be all bad?'

A paraphrasing of those statements into a geology/industrial minerals context might be an appropriate response to the next do-gooder, tunnel vision, environmentalist we encounter.

In recognition of so many from which I have so freely drawn for this presentation, I would be entirely remiss if I did not mention the article "Are they wearing you down?" in the December, 1992 issue of *Mining Engineering*, and a pearl therein submitted by one of our own, Lyn Bourne, who shared thoughts of apathy with us. A favorite near oxymoron of mine is, "Rampant Apathy." Are you/we guilty?

My "Show Your Pride" by vociferous professional proclamation as opposed to intravenous geology is not meant to be done at the expense of ethical conduct. Hardly! Pride and ethical conduct/integrity are completely complimentary. Humility is equally important but subjugation of the geologic profession to others is not to be tolerated.

William V. Knight addressed the image of geologists in the Executive Director's Column of the February, 1993 issue of *The Professional Geologist*. I am absolutely convinced that each of us could cite as many "for instances" as did Bill--plus have a few left over.

The image bashing occurs from many sources, much to my chagrin and much of it involuntarily (I hope) by fellow geologists. Economic conditions in recent years have created numerous suspect experts in fields heretofore quite restrictive. When feeding hungry mouths is part of the equation, "circumstances alter cases" as my mother so often said to me during my adolescent years, so necessity in lieu of greed may have inadvertently created negative images. Pride is also having the intestinal fortitude, character, integrity, whatever, to say, "I'm not qualified, but would be glad to recommend x, y, z, if you wish."

I may be the incurable optimist but to me/us, the industrial minerals geologists, the opportunities to cease relying on intravenous geology and become public, positive advocates for our profession and specialty, are abundant. I believe Jim Dunn was the first (to me at least) to say, "Behind every challenge/problem lies an opportunity." Therefore, our opportunities must be unlimited!

It is my contention that the industrial minerals producer of generally high bulk, low unit value product needs the services of competent "professionals" more so than the producers of mineral products with wider profit margins. Our services, competently provided and at a reasonable cost, combined with our willingness to tuck our own horn in political and civic arenas, have to augment our past history of intravenous geology and truly market or even showcase us as: "The Professional Geologist showing our Pride."

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# Flake Graphite and Zeolite Research Provides Potential Solutions to Domestic Problems

By

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## ABSTRACT

The current U.S. Bureau of Mines research program is addressing the recovery of flake graphite from kish, a steelmaking waste product, and the use of zeolites from abundant domestic natural deposits for efficiently cleaning up mining industry wastewater.

The United States is almost totally dependent on imports for its graphite needs, but this may change depending upon the results from a pilot plant being constructed by industry using Bureau technology. Standard mineral processing techniques were applied by the Bureau to recover high-quality flake graphite from kish. It was considered innovative enough to receive an R&D 100 Award in 1992, and its commercialization has the potential to supply the total U.S. demands for graphite many times over.

Zeolites have ion exchange properties similar to ion exchange resins, but are less expensive and available in large quantities. Samples of naturally occurring zeolites were tested for their efficiency in removing metal ions from synthetic and industrial waste solutions. The tests focused on defining their selecting, loading, eluting, and regenerating characteristics, and on developing a method for recovering the metal ions as added value products. The results showed that the removal of metal ions with zeolites from acid rock drainage (ARD) solutions is technically feasible and that this technique has the potential for being used in an integrated chemical treatment systems approach either as a primary or secondary cleaning step.

## INTRODUCTION

Recovery from secondary sources and wastes is an area of utmost national importance. It offers, through recycling, the potential for conserving national resources, reducing environmental impacts, and decreasing the Nation's reliance on imports for vital commodities. One of these commodities is flake graphite and its recovery from kish represents conversion of waste to a domestic resource.

The single greatest environmental threat from mining and mineral processing operations in the United States is that of contamination of water resources by acid-forming minerals, toxic metals, salts, particulates, and process reagents. This problem is magnified for these industries by the sheer magnitude of the mining operations, the generation of over a billion tons of waste annually, and the accumulation of over 50 billion tons from past operations.

Surface and ground water contamination from hard rock minerals mining and smelting operations has been the focus of millions of dollars in research but has resulted in no environmentally sound and cost effective solutions of the most serious problem; acid rock drainage (ARD) laced with toxic metals. A possible new approach for ameliorating this problem is through the use of natural zeolites which have the ability to extract heavy metal cations and to neutralize acids.

To demonstrate the technical feasibility of using a domestic steelmaking waste called kish as a source for producing a range of commercial-grade graphite products and abundantly available zeolites from natural deposits for treating ARD, the U.S. Bureau of Mines, Reno Research Center (RERC) is researching these options. A description of the research is presented as follows in Parts A and B with A focusing on graphite and B on zeolites.

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## PART A - GRAPHITE

### BACKGROUND

Graphite is a naturally occurring form of carbon with a unique combination of properties that make it indispensable in a very wide range of industrial and consumer applications. For example, the steel industry is dependent on graphite for making clay-magnesia, an alumina-bonded refractory for crucibles, bricks, facings, and coatings; the electrical industry uses graphite brushes in motors and generators, and electrodes in batteries; the transportation industry needs graphite for clutch and brake linings, and many other industries use graphite in a variety of products including seals, gaskets, lubricants, coatings, composite plastics and in the common pencil. Most importantly though is the fact that the United States is totally dependent on foreign sources from Mexico, China, Brazil, and Madagascar for this vital material. U.S. annual imports in 1991 totaled 33,000 tons at a cost ranging from \$110 to \$1,327 per ton depending on the type and grade of the graphite (Mineral Commodity Summaries, 1992).

### KISH

Bureau researchers at the RERC while conducting fundamental studies on molten metal systems observed that graphite could be grown under controlled operating conditions and that it was available from a renewable resource within the very industry that is its largest user. In the steelmaking process, molten iron tapped from the blast furnace contains dissolved carbon at a saturation concentration of about 6 percent. The liquid iron cools somewhat as it is transported and purified before entering the steelmaking furnace. On cooling, the iron cannot hold as much carbon in solution, and some of it comes out in the form of graphite flakes. Part of the graphite burns away, but much of it is wafted throughout the steel plant, where it falls as a continuous rain. More graphite, as shown in Photo 1, is skimmed from the surface of the molten iron just before it is poured into the steel furnace. This graphite material is a waste called kish that is contaminated by metallic iron, slag, and iron oxide and varies in size from large lumps, shown in Photo 2, to fines. For decades the coarse kish has been screened, as shown in Photo 3, to recover the iron lumps for recycle and to segregate the undersize fractions which are combined with fines collected in other plant cleaning operations and buried.

Kish is a potential resource of sufficient quantity to meet the U.S. demand for graphite, particularly the premium flake type, several times over. Because of differing practices at various steel plants, the composition and physical characteristics of kish are extremely variable.



Photo 1. Kish skimmed from molten metal.



Photo 2. Kish collection piles.

Some operations have air cleaning systems at transfer or at skimming stations that collect a baghouse product containing as high as 60 percent graphite. Other operations produce much more desulfurization slag relative to the graphite and their kish graphite concentrations may be as low as 10 percent. To determine whether kish could become a real resource, the U.S. Bureau of Mines engaged in research that resulted in the development of a process that demonstrated the technical feasibility of recovering graphite.





Photo 3. Screening of kish to recover large iron clumps for recycling.

## DESCRIPTION OF PROCESS

The graphite-from-kish process utilizes a nuisance waste of the steelmaking industry and produces flake graphite of quality generally exceeding that of the natural mineral. The process consists of screening, concentration by hydraulic classification, acid leaching to remove impurities, and final drying and sizing of the graphite product. Product purity can be tailored to user specifications to better than 99 percent. A schematic diagram of the process is presented in Figure 1.

In the initial screening operation, as shown in Figure 1, the large lumps of kish are screened to remove the oversized 1/4-inch particles. After the initial screening to reject particles over 1/4 inch, the undersize fraction is processed through a hydraulic classification, shown in Photo 4, to produce a float concentrate

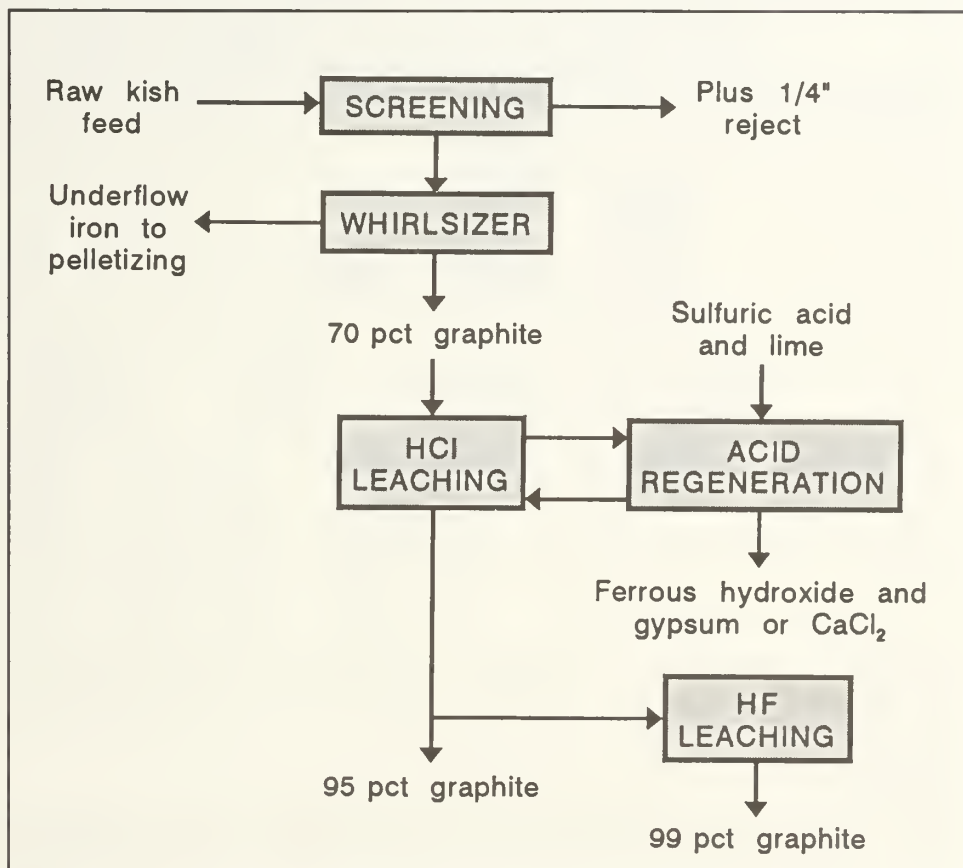


Figure 1. Flowsheet for recovering flake graphite from kish.

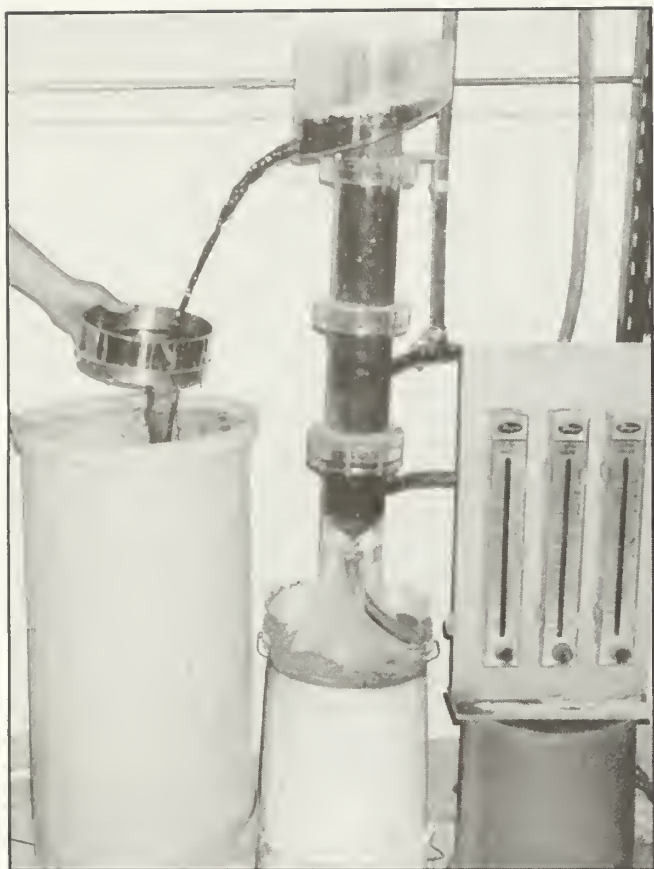


Photo 4. Hydraulic classifier for concentrating graphite.

that contains 70 percent graphite. The concentrate is then chemically treated, as shown in Photo 5, to produce graphite meeting user specifications. Leaching with percent hydrochloric acid gives graphite with purity up to 95 percent. If higher purity is required, additional leaching with hydrofluoric acid can achieve product purity greater than 99 percent carbon. The leached graphite is dried and screened to specified flake sizes which is suitable for a number of uses, as shown in Photo 6.

The process also includes regeneration of hydrochloric acid to minimize environmental effects and makes, by-products, a granular iron suitable for foundry feed, a recyclable hydrated iron oxide product, and wall board grade gypsum.

### LABORATORY TEST RESULTS

The kish process is simple and uses proven technology. Technical feasibility has been demonstrated at laboratory scale. Evaluation of the graphite products by a variety of industrial users has been overwhelmingly positive.

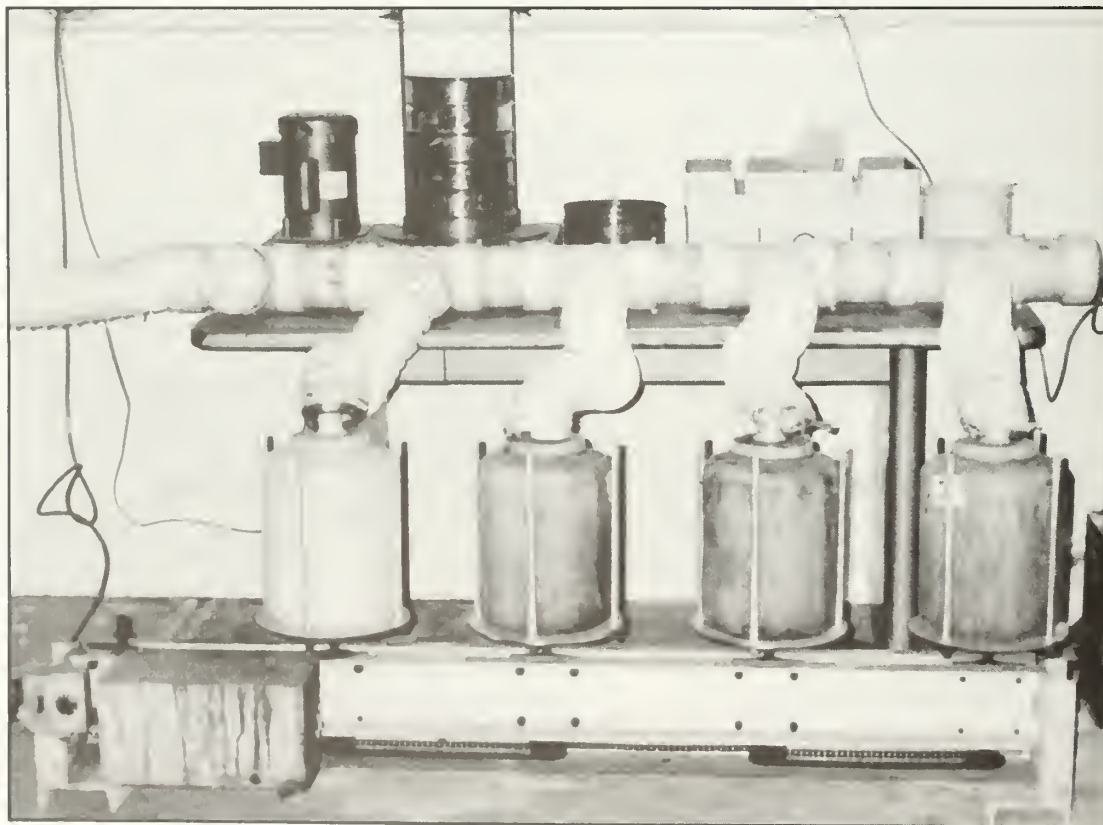


Photo 5. Chemical treatment for purifying graphite.

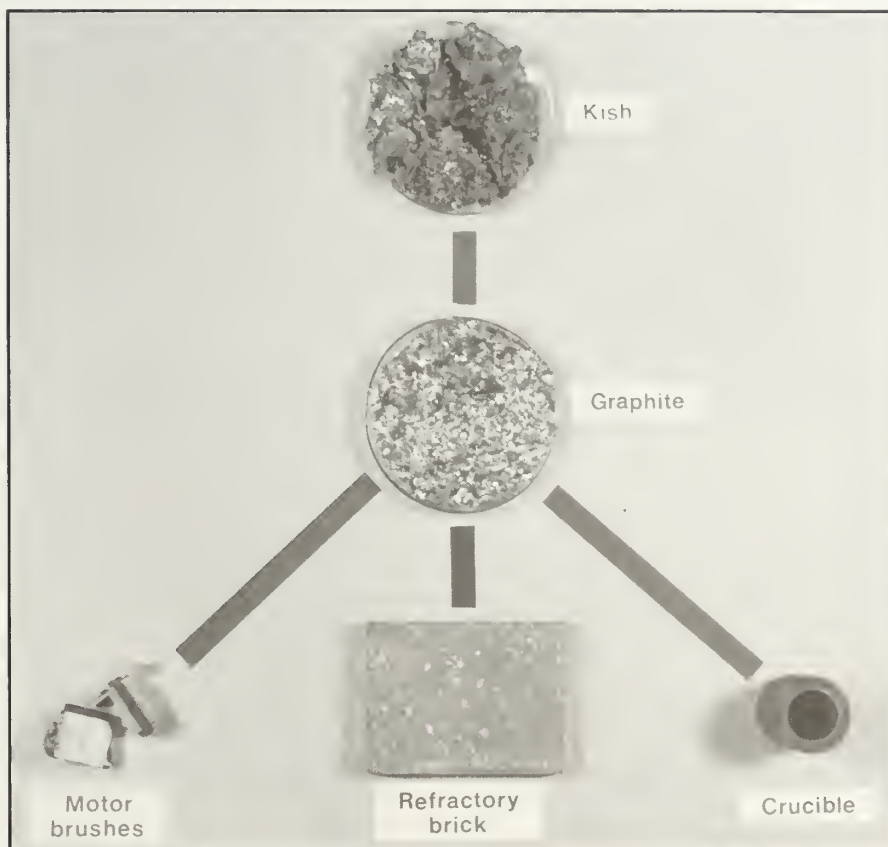


Photo 6. Kish, flake graphite, and uses for graphite.

ive. Kish graphite appears to be equal to and, in some uses, better than natural or synthetic graphite. Preliminary economic estimates based on laboratory test results indicate that processing costs are in the order of \$0.15 to \$1.50 per pound of graphite, depending on the grade of kish feed and product specifications. In comparison, the current market price for 99 percent graphite is approximately \$1.10 per pound.

### CURRENT RESEARCH STATUS

The U.S. Bureau of Mines has entered into a cooperative research and development agreement with two industrial cooperators to further evaluate this technology. Under this agreement, a major steel producer is construct-

ing a one-ton-per-day pilot plant at its site to obtain final engineering data to make a firm assessment of processing costs and to recover quantities of graphite product that will be used by the second cooperator, a graphite producer, to assess its usefulness and marketability.

### CONCLUSION

The graphite from kish process is technically, environmentally, and economically sound, and it makes an important contribution to the technology of graphite, which is indispensable to so many other products. Utilization of the kish will assure a supply of flake graphite for the long term since we estimate that sufficient graphite could be produced from domestic kish to exceed the current U.S. demand by a factor of 8.



## PART B - ZEOLITES

### BACKGROUND

Federal and state pollution control standards for heavy metal content of wastewaters from mines and mineral processing operations have become more stringent in recent years. Metal removal is generally done by precipitating hydrous oxides by CaO addition. Although this method is relatively simple and inexpensive, it has some disadvantages that dictate that a more efficient method needs to be developed. Two of the disadvantages are the sludge produced is voluminous and difficult to dewater, and the sludge is costly to dispose of as hazardous material. To help in this development, the U.S. Bureau of Mines is investigating the use of zeolites as an alternative method for removing heavy metals from wastewater. There are more than 30 distinct species of zeolite that occur in nature. However, only seven, mordenite, clinoptilolite, ferrierite, chabazite, erionite, phillipsite, and analcime occur in sufficient quantity to be considered as viable mineral resources (Vaughan, 1978). These minerals have ion exchange properties that are similar to ion exchange resins but are less expensive and readily available in large quantities. A potential treatment for removing metal cations from ARD to levels that meet water discharge standards would be to contact waste streams with zeolites. To show proof of concept of this technique, Bureau scientists and engineers are conducting research that is focused on determining the efficiency of several zeolites in removing a variety of metal cations from ARD to below drinking water standards and simultaneously reducing acidity.

### LABORATORY TEST PROCEDURE AND RESULTS

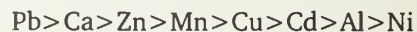
#### Material

Tests were conducted on five natural zeolites from three states in the western United States: four clinoptilolites, three of which were from California, one from New Mexico, and one phillipsite from Nevada. These zeolites were selected from a field of 30 zeolites because they were available in large quantities and also because in preliminary evaluation tests, they exhibited superior strength and loading characteristics. This information is significant as it will provide clues as to how a zeolite will perform, and also assist in process designing.

Solutions used in this investigation consisted of synthetic single-ion wastewaters that simulated the pH and the ion concentrations of typical ARD, and two typical ARD from abandoned copper mining operations. Metal ions of interest in these solutions were Al, Ca, Cd, Co, Cu, Fe, K, Mg, Mn, Na, Ni, and Zn.

### Shake Tests

To determine a selectivity series for the five zeolite shake tests were conducted by placing 2 g of each zeolite (minus 20, plus 60 mesh) in an Erlenmeyer flask with 20 ml of each synthetic single-ion solution. Samples from each flask were taken at different time intervals ranging from 1 min to 48 h. Test results showed that ion exchange took place within the first 4 h and that the selectivity series for some of the most toxic metal cations was as follows:



The order of selectivity was found to be the order most often encountered during testing of the five zeolite samples.

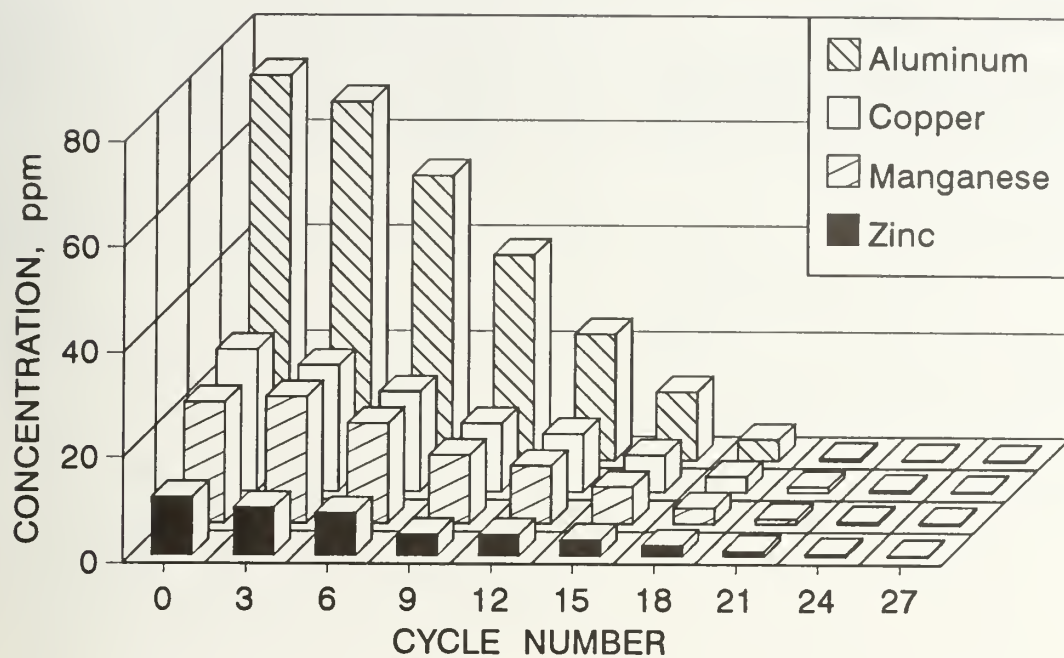
### Column Test

To further demonstrate the feasibility of this application, zeolites were tested in columns with both synthetic solutions and typical ARD to determine the lowest cation concentration that would be retained in the column underflows after repeated contact with batches of fresh zeolites. The tests were conducted in 30-cm by 1.5-cm glass columns loaded with 32 g of clinoptilolite using a starting solution volume of 1 L that flowed through the column at a controlled rate of 4 ml/min. Graphic representation of the effects for the processing of a typical copper mine wastewater for Al, Cu, Mn, Zn, Ca, Mg, and Fe are presented in Figures 2 and 3. The data show that zeolites will decrease the concentration of specific cation to safe levels. It was also observed that each zeolite performed differently. Consequently, the amount of each zeolite needed to do an identical job varied with zeolite performance. This was expected because of the differences in purity and in the amount of Na contained in each zeolite relative to Ca. Generally, a high Na zeolite will perform better than a zeolite containing higher Ca.

### Regeneration

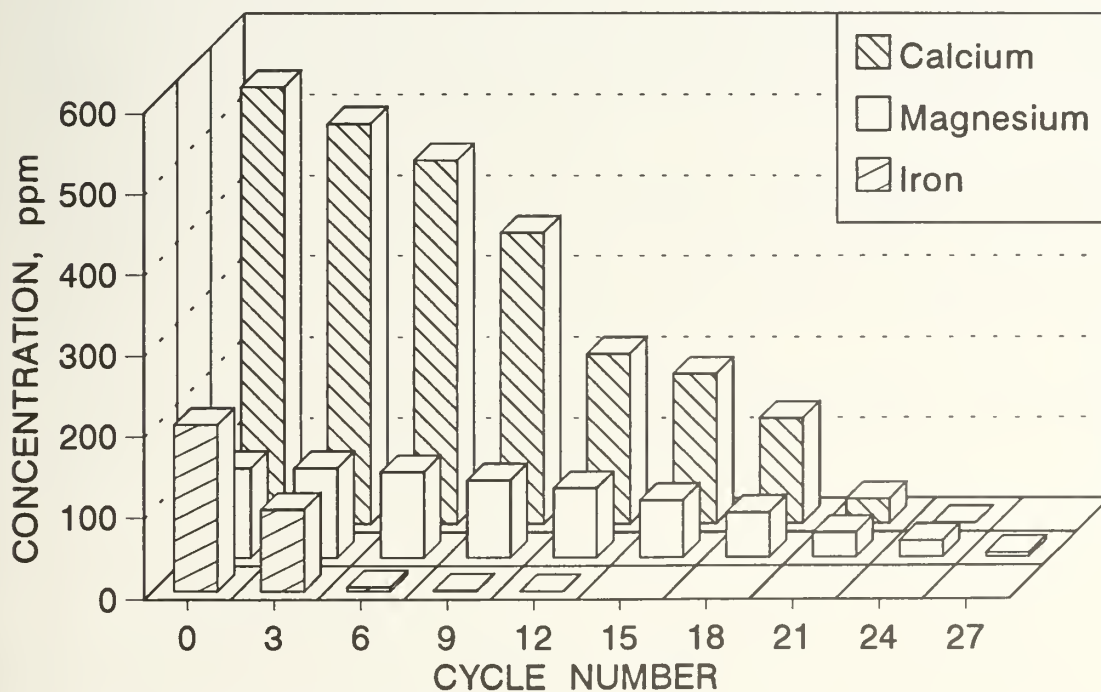
Zeolites loaded with heavy metals are hazardous material and must be handled appropriately to remove any danger to human, animal, and plant life. To eliminate this potential danger, regeneration of loaded zeolites was studied as a possible method for not only converting the zeolites for reuse but also for concentrating the metals for recovery. Regeneration studies were conducted in columns by contacting the loaded zeolites with a variety of chloride solutions containing 3 percent of the exchange ion being tested. The exchange ions tested were Na, Ca, Mg, and K. The sodium chloride solution was found to be the most effective for regeneration.





NOTE: Head sample at cycle "0"

Figure 2. Removal of metals from copper mine wastewater in column tests.



NOTE: Head sample at cycle "0"

Figure 3. Removal of metals from copper mine wastewater in column tests.

## PROPOSED FLOWSHEET

Based on the research findings, a proposed flowsheet, as shown in Figure 4, for treating ARD with zeolites was developed. The process is simple and uses processing unit operations that are proven and effective.

## CONCLUSION

Zeolites were shown to have the ability to remove the heavy metals from acidic wastewaters. Some of the advantages of using zeolites for treating ARD are as follows:

- Zeolites are inexpensive and abundantly available.
- Zeolites will reduce the concentration of most metals to drinking water standards.
- Zeolites can be regenerated for reuse.
- Metals originally in the wastewater can be concentrated for recovery.
- Zeolites will neutralize acidity.

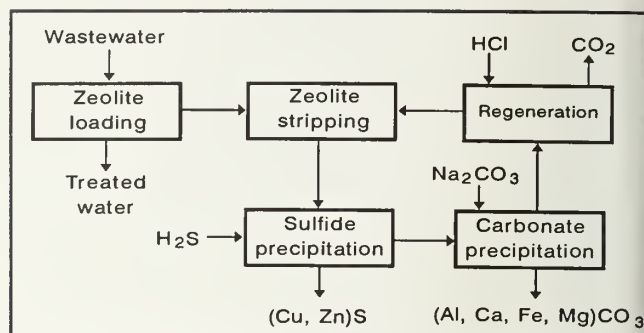


Figure 4. Proposed flowsheet for treating ARD with zeolites.

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- Vaughan, D.E.W., Properties of natural zeolites, in Sand, L.B. and Mumpton, F.A., eds., Natural Zeolites: Occurrence, Properties, Use, Pergamon Press, 1978, p. 353-355.



# Waste Material Resources in Virginia

by  
Palmer C. Sweet<sup>1</sup>

## ABSTRACT

Mining-related wastes, which are increasing, are being utilized more and more as valuable resources in Virginia. The Environmental Protection Agency (EPA) divides mining-related wastes into two categories: those generated from mineral extraction and beneficiation and those generated from mineral processing. Materials from both categories are produced in Virginia, where waste (by-product) materials are present at a variety of mining sites and processing plants; some of which have been exploited for various uses in the past and/or present. These materials include: used concrete recycled for roadbase material; pyrite coated with magnetite for use in portland cement; minor amounts of fly ash for use in concrete block, lightweight aggregate, and flowable structural fills; granite and diabase quarry fines for use as agricultural and asphalt filler; lime kiln dust for use in neutralizing and stabilizing coal refuse; soapstone aggregate for use in terrazzo heat retention panels; kaolin for use as a filler product and as an ingredient in white cement; slate quarry fines used as landcover and combined with aggregate for crusher run and as a filler in asphalt; and coal refuse for use as fuel in a lightweight aggregate plant. There are some materials available that have never been utilized, although several ideas were investigated to turn them into usable commodities. One such material is a high-alumina scrap produced as a by-product at a ferrovanadium processing plant. However, large quantities of waste materials from metal mining, industrial mineral, and fossil fuel operations remain to be disposed of in an environmentally safe and economic manner.

In 1989, almost one million tons of fly ash were produced from burning of coal at eight coal-fired power plants in Virginia. Present uses for this waste such as an ingredient in concrete block, concrete aggregate, and in structural fills cannot dispose of all the available material; however, increased use of fly ash as a soil/rock substitute for structural fills and embankments may solve the problem of its disposal. Another waste material is calcium carbonate precipitate paste produced at a lithium carbonate processing plant and presently being used for back filling an on-site inactive underground limestone mine.

Flue gas desulfurization (FGD) wastes in the form of  $\text{CaSO}_4$  will probably increase threefold. If this material contains a minimum of 95 percent gypsum and negligible chloride, it may have a value to a wallboard manufacturer as we move toward the year 2000. Thought must be given how this increasing waste can be disposed of in an environmentally safe manner.

## INTRODUCTION

In 1980 an amendment to the Resource Conservation and Recovery Act (RCRA) exempted mining wastes from regulation as hazardous waste, pending NGEPA studies. The RCRA is the primary federal law that governs the management of solid and hazardous wastes. EPA divides mining-related wastes into two categories: mineral extraction and beneficiation and mineral processing. In 1986 EPA determined that regulation of extraction and beneficiation wastes as hazardous wastes was not war-

ranted. Over the last several years, EPA determined that certain mineral processing wastes, such as flue gas desulfurization refuse is non-hazardous. In 1992 all RCRA bills containing provisions regulating mine wastes had these provisions stripped in committee and the bills never reached the House floor (Schiffries, 1992). Under the Clinton administration the RCRA, which is overdue for reauthorization, will probably not be addressed until late 1994 after Superfund is reauthorized. Mine waste measures will surely be included in any major reauthorization (Dwyer, 1993).



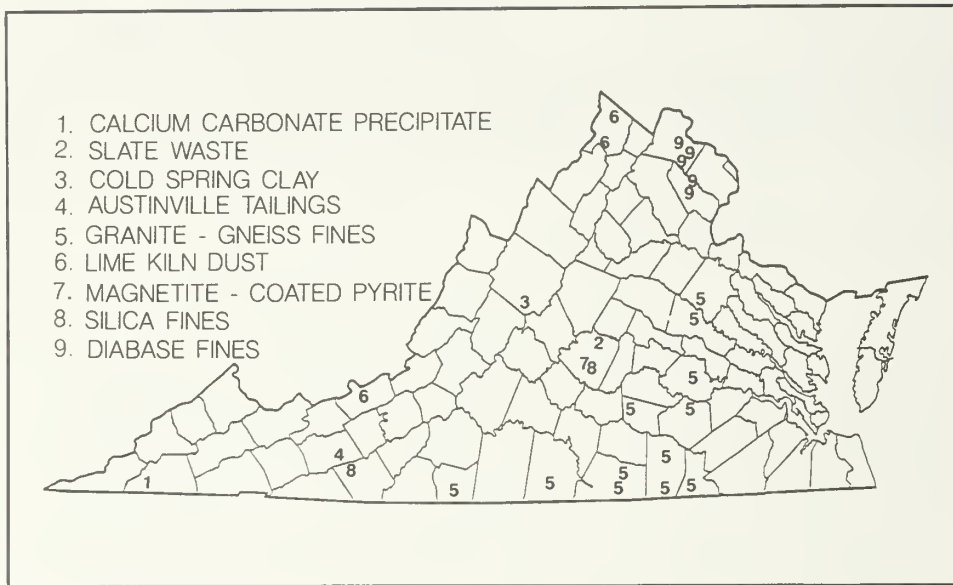


Figure 1. Some waste resource sites in Virginia.

Some determining factors in utilization of waste materials include the location of the material with respect to potential markets, chemical suitability of prospective material, and consistent quality and quantity. Some additional considerations include: production rates; processing and handling costs; availability of competing materials; seasonal adjustments; and the experience of design engineers, purchasing agents, contractors, legislatures, regulators, and other professionals. Some of the major mine and processing waste materials in Virginia, their location, present disposal and use, and some potential uses are discussed (Figure 1).

### AUSTINVILLE TAILINGS

A tailings pile of approximately 5 to 6 million tons of carbonate material covering about 52 acres remains on site of the former New Jersey Zinc Company property at Austinville in Wythe County (Photo 1). The company ceased operations in the early 1980s. These tailings remain from the processing of lead-zinc ore at this site for many years.

Independent chemical analyses from borings in the tailings pile indicate 20 percent  $MgO$ , 27 percent  $CaO$ , just over 2 percent  $SiO_2$  and less than 4 percent  $Fe_2O_3$ . James River Limestone Co., Inc. purchased the site and opened a quarry on the property just north of the tailings pile. The company, in addition to aggregates, also markets the tailings, as is, for agricultural use.

### BRICK FINES

During the loading, firing, and removing of bricks in a kiln, some bricks are broken and fired bits of clay-shale are also produced. In most cases, pieces of brick and coarse fines are returned to the mix. Some companies will purposefully crush the broken and reject brick in a jaw or

ball crusher to produce coar and fine material. The coarse fraction is marketed for use as ornamental aggregate, and fines so for use as a soil conditioner to a in draining athletic fields and f use on tennis courts. Some us for brick fines (less than 6-mes) other than returning them to t mix, have been suggested by t Minerals Research Laboratory Asheville, North Carolina. Oth uses, in addition to those alrea noted, include: use as a filler the manufacture of block or ligh weight aggregate; as a fi pozzolonic material; as an a phalt filler; in potting soil f drainage; as a mix with clay make quarry tile; and as an inse

ticide carrier, if porosity specifications can be met (M. Garska, 1992, written communication). Virtually all t brick plants in Virginia have some brick fines; in t majority of cases, they are disposed of by being return to the mix.

### CALCIUM CARBONATE PRECIPITATE PASTE - TAILINGS

Cyprus Foote Mineral obtains lithium carbona ( $LiCO_3$ ) from brines in Nevada and also imports son lithium carbonate from Chile. Calcium hydroxide, o tained from an in-State lime producer, is mixed with t  $LiCO_3$  to produce lithium hydroxide powder, used many multipurpose grease applications. A waste produ is calcium carbonate precipitate paste which contains 4 to 50 percent  $CaCO_3$ , 3 to 6 percent  $Ca(OH)_2$ , 40 to 4 percent water and some lithium. This material is dispos



Photo 1. Tailings from the former operation of New Jersey Zinc Co located at present site of James River Limestone Co., Inc., Austinville, Wythe County.



of in an inactive, slope-entry, underground limestone mine at the rate of 225 tons per week (Photo 2). Because of its lithium content, the material may not have a use as a fertilizer; however, there may be some potential to utilize it to neutralize and stabilize coal refuse in the Southwest Virginia coalfields.

Approximately 2 million tons of tailings produced at the plant from 1953 until the early 1970s, when the process changed (requiring less limestone), are stockpiled on the site. Average chemical analysis of these tailings by weight percent follow:

SiO <sub>2</sub>	20.44	SO <sub>4</sub>	0.53
Al <sub>2</sub> O <sub>3</sub>	11.59	Li <sub>2</sub> O	0.52
Fe <sub>2</sub> O <sub>3</sub>	2.79	Na <sub>2</sub> O	0.23
CaO	59.47	K <sub>2</sub> O	0.16
MgO	1.90	L.O.I.	13.10

Presently the old tailings are stored in several piles on the property and on a large 25-acre site to the south of the plant. The large site south of the plant is stabilized and monitored for any possible nearby stream contamination. The piles of tailings near the plant are being consolidated.

### FLY ASH

Fly ash is a combustion by-product produced by the burning of coal in coal-fired power plants. Eight power plants in Virginia produced about 920 thousand tons of fly ash in 1989 (Figure 2). This is small compared to the approximately 70 million tons of fly ash produced in the United States in 1990 (Tyson, 1992).



Photo 2. Calcium carbonate precipitate paste in underground limestone mine at Cyprus Foote Mineral, Sunbright, Scott County.

The American Coal Ash Association, Inc. (ACAA) promotes the use of coal combustion by-products in applications that are commercially effective, technically proven, and environmentally sound.

#### Uses of fly ash include:

- \* Cement and concrete products (reportedly 50 percent of cement produced today has fly ash in it).
- \* Soil and rock substitute in structural fills and embankments-as a borrow material that is compacted and can support structures. Fly ash, when achieving required levels of compaction may offer site specific advantages over soil and rock, such as low unit weight and availability. Both structural fill and embankments are high-volume uses of fly ash.

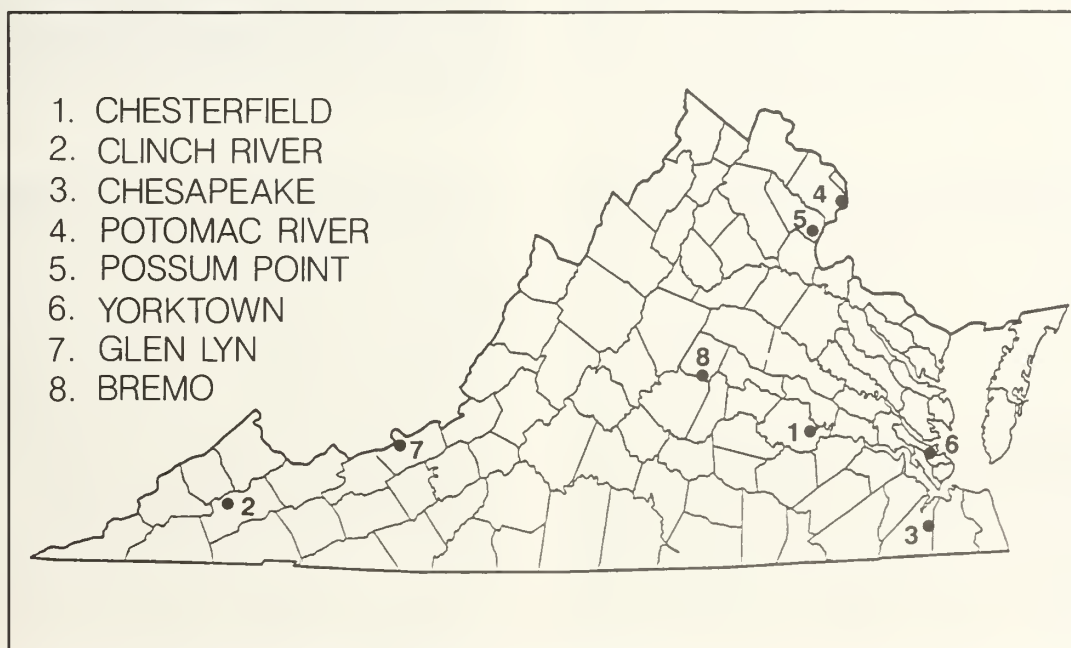


Figure 2. Location of eight coal-fired power plants (1989) in Virginia.

- \* Roadbase and subbase material.
- \* Grouting.
- \* Filler in asphalt mixes.
- \* Traction material for highways.
- \* Soil conditioner as source of iron and alumina.
- \* Combination with cement kiln residues to produce mineral wool.

#### Potential problems:

- \* Location of the supply related to the market.
- \* Variable composition of the original coal.
- \* Total amount of ash available.

An example of an old fly ash problem is the contamination of groundwater from the Chisman Creek site on Wolftrap Road, York County in eastern Virginia. This 27-acre area originally consisted of borrow pits that were used as a dump area for 1.3 million cubic yards of fly ash and burned petroleum coke from the Yorktown generating station. Because of complaints by nearby residents of discolored water, the site was investigated. It was concluded that contaminated water was moving laterally from the pits into the groundwater and pollutants such as vanadium, selenium, cadmium, nickel and arsenic were identified in the sediment, water column, and aquatic life in Chisman Creek. This was one of the nation's first hazardous waste sites eligible for federal assistance and one of the first EPA Superfund sites to be reclaimed. Work began on the site in late 1987. The pits were capped with clay and soil and planted with grass; drains were installed around the pits and continuous monitoring was placed in effect. Today the capped areas serve as sites for two recreation parks, namely Wolf Trap Park and Chisman Creek Park (Photo 3). The monitoring at the sites is presently minimal due to the good water quality. The local municipality routinely tests the water.



Photo 3. Chisman Creek Park, reclaimed fly ash pit, near Grafton, York County.

Presently, Virginia Power burns only coal at its Yorktown facility and is storing both bottom ash and fly ash on a 45-acre site about 2 miles south of the power plant. The ash is transported by truck, compacted and stored in 3-acre "cells" that are underlain by a 5-foot layer of bentonite clay (Photo 4). Each cell contains about 90,000 cubic yards of ash. After the ash is dumped and rolled, it sets up very hard, and as the cell is filled, it is covered with a 2-foot layer of soil and is planted with grass. The final product is essentially a 20-foot high, long flat plateau. Approximate cost of preparing a cell to store the ash is half a million dollars (L. Johnson, 1992, personal communication). Some of the ash will be "mined" from the cells and utilized in the local area of York County. The fly ash is mixed with cement and water in a concrete truck, to produce a flowable fill, for use as subbase for concrete slabs or asphalt cover.



Photo 4. Fly ash "cell", with bottom 5-foot layer of bentonite clay, south of Yorktown power plant, York County.

At the Chesapeake plant of Virginia Power, fly ash is mixed on site with portland cement, surfactant foam, dry catalyst and accelerators by Agglite Corporation (Photo 5). These ingredients are mixed with a screw auger



Photo 5. Chesapeake Plant of Virginia Power, with storage pile of coal in background to the left, City of Chesapeake.



combined with water and pelletized. It is a cold-bonded process, with no external heat, as only the heat of hydration released by the combination of fly ash and cement is utilized. The "manufactured aggregate" is spherical, is lightweight (58 lbs./cubic foot) and has physical properties necessary to meet the three basic ASTM specifications for lightweight aggregate; C-330 for structural concrete, C-331 for concrete masonry units and C-332 for insulation concrete. The lightweight aggregate is stored in on-site silos. Markets for this product are for use in manufacturing concrete block in Virginia and North Carolina. Ash from this site is also used as a compacted sand substitute as well as a flowable structural fill. The flowable fill material is mixed in a concrete truck and is applied on-site just like concrete. A large quantity of flowable fill (approximately 9,000 cubic yards) was used as a base material under concrete slabs for vertical support beams at the recently constructed Harbor Park (Photos 6 and 7).

Other potential uses of the fly ash include the filling of borrow pits and for reclaiming surface coal mines. Borrow pits, in the Coastal Plain province, can be lined



Photo 6. View of Harbor Park, future home of the Tidewater Tides, Triple-A baseball farm team of the New York Mets, City of Norfolk.



Photo 7. Flowable fill, between support beams, Harbor Park, City of Norfolk.

with clay, filled with ash, covered with soil, seeded and brought back to their original contour level. Buchanan (1993) also notes that consideration is being given to utilizing fly ash in reclaiming surface coal mines. At the present time (February, 1993), the Virginia Department of Waste Management is debating fly ash regulations, which would treat ash as a waste product if it were used in making another product.

Wise County, in southwestern Virginia, has a current ordinance that states that companies wanting to dispose of fly ash, must get permission from the board of supervisors in order to do so. Several alternative ordinances have been debated by the county board of supervisors for months. Ordinances would ban fly ash or only allow a percentage to be returned, according to the volume of coal mined in the county. It is interesting to note almost 12 million tons of coal were produced in Wise County in 1991. The proposed construction of a \$400 million cogeneration plant in Wise County and its economic impact on the local economy may lead to elimination of any further discussion of changing the ordinance (Buchanan, 1993).

## COLD SPRING CLAY DEPOSIT

The Cold Spring kaolin deposit, located near Big Levels in Augusta County, was last operated in 1951. White kaolinitic clay was first mined at this site in 1912 for use as a paper filler. By the late 1940s, the better quality clay had been mined, and production after this time was for use in oil paints and for camouflage paint for wartime use. Over the years, as much as 175,000 tons of material may have been produced. An old chemical analysis of the material indicates 39+ percent  $\text{Al}_2\text{O}_3$ . A sample collected in 1988 was analyzed by X-ray fluorescence (XRF), at the Division of Mineral Resources laboratory, and indicates 28.9 percent  $\text{Al}_2\text{O}_3$  (Sweet and Giannini, 1990).

Today the site contains large spoil piles of kaolinitic material mixed with occasional bits of bauxite. In the early to mid-1980s, a company utilized some of this waste material as a component in a filler-extender product and also for use in the manufacture of white cement.

## FINES

Processing of rock materials, by crushing and screening to meet specifications for clean, uniformly sized aggregate, generates 5 to 15 percent dust-size fines as a by-product (-200 mesh). These fines (classifier tailings) are presently a waste product, and calculated as a part of the production cost, which must be handled and disposed of. Fines are produced in both dry and wet processes, which are determined by the types of stone marketed. Wet-processed fines are usually collected in settling ponds (pond screenings). Major uses for dry and wet fines have been for general fill and reclamation.



Stokowski (1993) notes a long list of potential products from pond screenings that include agricultural, ceramic, chemical, cleansers, construction, industrial mineral and precious metal, mineral coatings, fillers, pigments, and pollution control and safety products. Numerous articles have suggested the value of powdered rock in replenishing essential minerals, improving existing soils, and creating new topsoil. Successful crop production has been carried on for years in regions of naturally fertile soils where geological processes provide a continuous supply of nutrients. The processes include a complex geochemical balance of all 92 elements present in minerals (Leonardos and others, 1987). Able (1992) notes the benefits of adding rock dust to soils; it can improve soil quality; reduce the need of soluble chemical fertilizers; improve resistance of plants to insects, disease, and fungus; improve the nutrient density and flavor of food and feed; regenerate damaged forest ecosystems; and preserve air and water quality. As for application rates of rock dust for remineralization of soil, the consensus of opinion through numerous articles indicates the standard is about 10 tons per acre. As much as 20 tons per acre is recommended for very poor, depleted soils (Able, 1992).

In 1991, more than 30 million tons of aggregate were produced from basalt, diabase, granite and greenstone (metabasalt) in the Commonwealth of Virginia. Using even a median figure of 10 percent fines, this equals about 3 million tons of rock dust produced in that year.

## DIABASE

More than 8 million tons of diabase were produced during 1991, all production was from northern Virginia. A large amount of fines resulted from these operations, especially from production of "stone sand," which is a product from several quarries mainly for use in asphalt. Some of these fines are utilized in asphalt as well as for roadbase material. Minus 200 mesh material is the main waste and has no market, because only a limited amount can be used as an extender in asphalt or in roadbase material. Possible uses may be as a filler in charcoal briquettes, as an ingredient in flowable fill, and as an ingredient in the manufacture of clay pigeons.

At quarries where stone sand is not produced, dry fines are being marketed for use as "bedding" for large diameter concrete pipe and buried cables. One project in the Leesburg area of Loudoun County used 150,000 cubic yards of diabase fines for bedding around pipes for a municipal water supply project.

## GRANITE-GNEISS

Many of the granite quarries in the southern Piedmont produce "stone sand" utilizing a wet grinding process. Their resulting fines from these operations are presently being stored in settling ponds on the property.

Potassium, one of the three main plant nutrient fertilizers is present in potassium silicates (orthoclase feldspar), which are common in igneous and metamorphic rocks. When these rocks weather, potassium is released not only from orthoclase feldspar but also from minerals such as sylvite, which contains about 63 percent  $K_2O$ , and kainite, which contains about 19 percent  $K_2O$ . Some whole-rock chemical analyses for granitic material in Brunswick and Nottoway counties in the southern Piedmont province of Virginia indicate that they contain more than 10 percent  $K_2O$ . Granite fines may be suitable as a low-grade fertilizer or as a soil re-mineralization ingredient. This material needs to be dry in order to be marketed, thus one of the main problems is that the fines are produced wet because of the more economical mill process and would have to be dried before they could be sent to market. Another potential market brought on by the environmental concerns is the use of fines for the remineralization of golf courses, which would lead to a reduced use of chemical fertilizers. Another use for granite fines has been at farms for use in "loafing" pens for dairy cows, in horse arenas, and on farm roads (Photo 8 and 9). Another use for granite fines that has been investigated is as a binder with charcoal in making charcoal briquettes. The specifications required for this use are that the fines be dry and be restricted in size to be larger than a buckwheat grain.

Several quarries produce large quantities of fines and analyses of several samples from each quarry show that the rocks contain from 2 to 4 percent  $K_2O$ . A quarry in Henry County has a large amount of these fines, but the potassium content is not high enough to allow use as a low-grade agricultural material. These fines may be used for overall remineralization by themselves or in combination with carbonate fines. About 20,000 tons of material at this quarry are extracted yearly from the settling ponds and piled to dry (Photo 10). Some of the material has been mixed with sand and lime to produce foundation support (bedding) for buried concrete pipe. It will pack down but can also quickly break down physically. The fines from this quarry have also been marketed as an extender in asphalt, used in base material for patios and used by landscaping companies to break up the clay in order to condition soils.



Photo 8. Granite fines used in a horse arena at Horseshoe Hill Farm, northwest of Ashland, Hanover County.



Photo 9. Granite fines used on a farm road at Horseshoe Hill Farm, northwest of Ashland, Hanover County.



Photo 10. Quartz monzonite gneiss fines at Wilson Quarries, Henry County.

Another use of the granite fines has been as a base material in landfills. Landfill bases are normally lined with clay. However, in a landfill in Chesterfield County, the clay is covered with a one-foot layer of granite fines, then a plastic liner is added and covered by another clay layer (Photo 11). This landfill is adjacent to a granite quarry, which allows for an accessible source of granite fines.



Photo 11. Landfill in which the underclay is overlain by one foot of granite fines, west of Chester, Chesterfield County.

## SILICA

Kyanite Mining Corporation, in Buckingham County, produces sand as a by-product during the processing of kyanite (Photo 12). This material is sold for blasting sand, masonry and golf course sand, play sand, foundry sand, and as sand for lining pipes in order to extend their life.

Similar silica (all -200 mesh) is produced at a quartzite quarry in Wythe County near Sylva. At the present time there is no use for this material and large stockpiles are on site.



Photo 12. By-product sand at East Ridge plant of Kyanite Mining Corporation, Buckingham County.



## Flue Gas Desulfurization (FGD) wastes

EPA has concluded that flue gas desulfurization wastes in the form of "synthetic gypsum" do not exhibit hazardous characteristics. There are about 16 million tons of FGD waste produced each year, in the United States, and that figure may be 50 million tons by the year 2000. Presently some of the waste is sold for use in cement; it is used in wallboard (when the gypsum content is at least 95 percent); and used for reclamation of abandoned coal mines. An important consideration in the use of gypsum for the manufacture of wallboard is the percentage of chloride present as it may cause deterioration of nails and screws that secure the wallboard. Some of the material has been rolled in balls and sold for use as a crushed stone substitute. This "synthetic gypsum" is used as a retarder in cement and may also have a use as "land plaster" to improve soil conditions for the peanut industry. Cost to put FGD waste in landfills is \$6 to \$10 per ton and estimates for cost of disposing of this material in the future could range from \$20 to \$25 per ton.

### Lime Kiln Dust

Lime kiln dust is a by-product of calcining lime in a rotary kiln (Photo 13). The gases and dust are directed to a baghouse, where the dust is collected and the gases are vented into the atmosphere. The dust particulate material consists of 15 to 18 percent calcium oxide ( $\text{CaO}$ ), 70 to 75 percent calcium carbonate ( $\text{CaCO}_3$ ), which makes the dust highly alkaline (up to 12.4 pH), and the remainder is fly ash, high in silica and alumina. When 2 percent by weight of lime kiln dust is added to acidic coal refuse generated at coal preparation plants, there is an increase in pH and alkalinity, bacterial growth is inhibited and the formation of acid water is drastically reduced (Rich and Hutchison, 1990).



Photo 13. Rotary kiln which vents to the baghouse, where lime kiln dust is recovered, APG Lime Corporation, Kimballton, Giles County.

At a locality in Nicholas County, West Virginia, lime kiln dust is trucked, from APG Lime Corporation in Giles County, Virginia, to the preparation plant and loaded into a dust bin. From the bin, the lime kiln dust is metered onto the coal refuse belt by means of a variable rate screw conveyor. The treated coal refuse is trucked to mined-out areas where a cell (disposal site) is created. The dust not only neutralizes the coal refuse but also stabilizes the material, allowing dozers to easily push it up into piles. In a matter of a couple of days, the refuse will firm up enough to drive trucks on it.

Some of the economic effects of utilizing lime kiln dust include requiring less equipment to maintain a refuse cell, elimination of rock bridges to support trucks while moving coal refuse around, and the extended life of the cell.

There is considerable interest in using lime kiln dust at sulfide metal-mining operations to neutralize tailing waste rock, etc. On a trial basis, lime kiln dust is being utilized on tailings embankments at Kennecott's Ridgeway Gold Mine in Ridgeway, South Carolina.

### Magnetite-Coated Pyrite

Kyanite Mining Corporation in Buckingham County quarries a kyanite-bearing quartzite, which contains some pyrite. After the material is crushed in a jaw crusher and a rod mill, froth flotation is used to remove the kyanite. It is then dewatered and dried. The high temperature of the drier converts the sulfides (pyrite) to oxides. Pyrite ( $\text{FeS}_2$ ) or ferric oxide is converted to magnetite ( $\text{Fe}_3\text{O}_4$ ), ferrous iron oxide. The material is removed with magnetic separators and stockpiled (Photo 14). The material was used as the iron ingredient at a plant producing portland cement. It was discovered that since the mag-



Photo 14. Stockpile of waste magnetite at Kyanite Mining Corporation, Buckingham County.



was not "through the body" and contained pyrite, that was introducing sulfur to the cement product. Presently the material is being marketed for use in artificial heating briquettes (used in gas-fired grills), for use in exothermic compositions, and as a colorant. Potential use is still being investigated as an ingredient in cement and as a heavy media for cleaning coal or in other uses where the magnetic properties could be utilized. Another potential use uncovered during the study was as a heavy filler in "original" charcoal briquettes.

## RECYCLED CONCRETE

Crushed, sized concrete will pass specifications for base material in road construction. In the past, broken concrete was crushed and recycled for use in base material in northern Virginia. The operation became uneconomical because of the inconsistency of concrete that was applied to the crusher, and the presence of iron rods (rebar) in the concrete also became a problem. Presently several companies in the Hampton Roads area of eastern Virginia are processing broken up concrete for construction jobs as needed. Several years ago a concrete recycling operation in Ohio was producing five sizes of material; the product ranged in size from 4 inches in diameter to sand-sized material. This operation used a magnetic head pulley to remove rebar broken out by the jaw crusher. After secondary crushing, a cross belt magnet was used to remove free iron.

## SLATE WASTE

Virginia produces approximately 100,000 tons of slate annually which is mainly sold as roofing slate. In the production of roofing slate, 80 percent or more of the slate is unfit for roofing shingles and is utilized for floor tile, various pieces of architectural slate, and then for flagging.

The rejected material from manufacturing these products is sent to the aggregate plant, and local road aggregate is produced. The aggregate material ranges in size from 3/8" to fines, some of which is put to use around the plant as landcover or "hole filler" and some is sold for this same end use. Some fines can be put back in with the aggregate for crusher run, some can also be used as a filler in asphalt for paving.

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# Production and Marketing of Perlite in the Western United States

by

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## ABSTRACT

Perlite is rhyolitic glass with 2 to 5 percent by weight (wt.%) bound water held within the silicic-glass structure. It is often distinguished by vitreous, pearly luster and concentric perlitic fractures ("onionskin"). Occurrences worldwide are associated with Tertiary to middle Quaternary volcanic rocks. Perlite is in silicic domes, plugs, laccoliths, flows, vitric tephra, chill margins of dikes and sills, and welded ash-flow tuffs. It is a hydrated volcanic glass formed through secondary alteration of obsidian by the incorporation of water into the glass/silica structure. Post-emplacement hydration (weathering) of cooled glasses by meteoric water is the principal alteration process, but some hydration by magmatic or meteoric water during or shortly after emplacement, or hydration by water exsolved during cooling may occur. Commercial "perlite" is any volcanic glass that expands or "pops" when heated quickly to plasticity while evolving steam and thus forming a lightweight, frothy material. The expansion temperature typically ranges from 1,100 to 1,500°F. An expanded volume increase of 10 to 40 times the original volume yields expanded densities of 1.5 to 11 pounds per cubic foot (lbs/ft<sup>3</sup>).

Perlite is mined by eight companies at 10 operations in six western states. New Mexico accounts for more than 80% of the total tonnage mined. The rest comes from Arizona, California, Colorado, Idaho, and Nevada. In 1992, domestic production was 571,000 short tons (st), domestic apparent consumption was 591,000 st, and the value of crude perlite was \$15.3 million. In 1991, with about the same production and price of crude perlite, the gross value for expanded perlite was \$101.7 million. Perlite exports in 1992, primarily to Canada, are estimated at 30,000 st; and imports, from Greece, are an estimated 50,000 st.

In 1992, 70 plants in 33 states expanded crude perlite. Construction uses of expanded perlite accounted for 66% of total domestic sales. Expanded perlite used as filter aid accounted for 15%. All other markets, including use as a filler and in agriculture, accounted for 19%. Leading states for expanding perlite, ranked by order of sales, were Mississippi, Pennsylvania, California, Illinois, and Georgia. Domestic perlite encounters transportation disadvantages in some areas of the eastern United States compared to perlite imported from Greece. However, western U.S. perlite exports to Canada offset this in large part, and net import reliance for perlite is about 3% of domestic consumption.

Perlite grab samples were tested at the New Mexico Bureau of Mines and Minerals Resources (NMBMMR) for their basic suitability in horticulture, construction, filter aids, and fillers/extenders using Perlite Institute techniques modified by the NMBMMR. Most commercial perlite ranged from 2.5 to 3.0 wt.% bound water for all major types (classical, granular, and pumiceous). Expanded density varied widely, but the lowest density of 1.9 lbs/ft<sup>3</sup> was for granular. Average brightness of expanded perlite was 47.6 to 69.3%. Nonexpansibles, commonly obsidian or "dead" perlite, ranged from 18 wt.% to less than 1 wt.%, with granular perlite generally the lowest. Compacted density was not related to either perlite type or nonexpansibles present. Sieve analyses of the -50+100 mesh product showed that, in general, pumiceous perlite produces more fines and classical and granular perlite average 60 to 80% -30+100 mesh after expansion. Samples were tested for crystalline silica that ranged from below the detection limit of 0.5 wt.% to nearly 0.2 wt.%, but most tested below 0.5 wt.%. Although quartz content can be lowered in the expanded product by the expansion process, producers can further lower crystalline silica in the product by mixing low-quartz crude with high-quartz perlite before expansion. Chemical analysis by x-ray fluorescence confirms the rhyolitic composition of perlite, but indicates that surface weathering may increase the concentration of some elements, such as potassium and calcium, by infilling cracks or fissures developed during or after perlite emplacement.



## INTRODUCTION

The use of perlite, a distinctive volcanic glass, dates back to at least the late 19th century and perhaps the 18th century (Howell, 1974), but some authors suggest that perlite was recognized much earlier, perhaps in the third century B.C. (Kadey, 1983). Most definitions identify perlite by the presence of a vitreous, pearly luster and the characteristic concentric or arcuate perlitic fractures (Breese and Barker, 1993). However, arcuate fractures in perlite need not be megascopic and textures of perlite range from dense to highly vesicular to pumiceous. Perlite is distinguished petrologically from other natural glasses by a silicic, rhyolitic composition and 2 to 5 wt.% total chemical water held within the glass structure, and often by the presence of a pearly luster and perlitic ("onion-skin") fractures. Occurrences worldwide are associated with Tertiary through middle Quaternary volcanic rocks and with the glassy parts of silicic domes and flows, vitric tephra, chill margins of dikes and sills, and welded ash-flow tuffs. Perlite is less commonly associated with volcanic plugs and laccoliths.

Perlite is mined by eight companies at 10 operations in six western states. New Mexico accounts for about 80%

of the total tonnage mined. The remaining 20% comes from Arizona, California, Colorado, Idaho, and Nevada. In 1992, domestic production was estimated to be 571,000 short tons (st) and apparent domestic consumption was 591,000 st. Perlite exports, primarily to Canada, were estimated to be 30,000 st, and imports, primarily from Greece, were estimated to be 50,000 st (Bolen, 1993). Domestic perlite encounters transportation disadvantages in parts of the eastern United States compared to Greek imports. Western U.S. perlite exports to Canada offset this in large part.

In the United States, most perlite is shipped to processing plants before it is expanded. Crude perlite expands to a glass foam, or "pops," when heated quickly, plasticity while evolving steam. In 1992, 70 plants in 35 states expanded perlite (Bolen, 1993, personal communication; Figure 1, Table 1). Construction uses of expanded perlite accounted for 66% of total domestic sales. Expanded perlite used as filter aid accounted for 15% while use as fillers and in agricultural and other markets accounted for 19%. Leading states, in descending order of sales, were Mississippi, Pennsylvania, California, Illinois, and Georgia (Bolen, 1992).



Figure 1. Index map of perlite expansion plants in the United States.

Table 1. Operating perlite expanders in the United States in 1992.

<u>State</u>	<u>Company</u>	<u>State</u>	<u>Company</u>
<b>Alabama</b>	W R Grace and Company Armstrong World Industries	<b>Massachusetts</b>	Whittemore Perlite Co. Inc.
<b>Arizona</b>	Therm-O-Rock Industries Inc.	<b>Michigan</b>	Harborlite Corp.
<b>Arkansas</b>	Strong-Lite Products	<b>Minnesota</b>	USG Interiors Inc.
<b>California</b>	Nor-Cal Perlite Inc. Paramount Perlite Co. Inc. Redco Cal-Shake, Inc. International Permalite Co. Harborlite Corp. Aztec Perlite Company	<b>Mississippi</b>	Manville Products Corp. USG Interiors Inc.
<b>Colorado</b>	Dicaperl Persolite Products Inc.	<b>Missouri</b>	Bourk Company
<b>Florida</b>	W R Grace and Company Chemrock Corp. Armstrong World Industries Airlite Processing Corp.	<b>Nevada</b>	U.S. Gypsum Wilkin Trucking and Mining
<b>Georgia</b>	Armstrong World Industries Eastern Industrial Minerals	<b>New Jersey</b>	Schundler Company
<b>Idaho</b>	National Perlite Products Co.	<b>New Mexico</b>	Silico
<b>Illinois</b>	Silbrico Corp. Strong-Lite Products Corp. of Illinois Manville Products Corp.	<b>New York</b>	Scolite International Corp.
<b>Indiana</b>	U.S. Gypsum National Gypsum Company Grefco Inc. Chemrock Cryogenic	<b>North Carolina</b>	Carolina Perlite Co.
<b>Iowa</b>	National Gypsum Co.	<b>Ohio</b>	PVP Industries Inc.
<b>Kansas</b>	Lite Weight Products Inc.	<b>Oregon</b>	Supreme Perlite Co.
<b>Kentucky</b>	International Permalite Co.	<b>Pennsylvania</b>	Nord Perlite Co. Armstrong World Industries Inc. Pennsylvania Perlite Corp. Therm-O-Rock Pennsylvania Perlite Corp. of York, PA
<b>Louisiana</b>	Filter-Media Company of Louisiana Inc.	<b>Tennessee</b>	Chemrock Corp.
<b>Maine</b>	Chemrock Corp.	<b>Texas</b>	South Texas Perlite W R Grace and Company Filter Media Inc. Perlite of Houston Inc. Nord Silflo Inc.
		<b>Utah</b>	The Pax Company
		<b>Virginia</b>	Manville Roofing Systems
		<b>Wisconsin</b>	Midwest Perlite Co.
		<b>Wyoming</b>	Harborlite Corp.

Source: Bolen, 1992; Bolen, 1993, personal communications

## GEOLOGY

Perlite is one of the natural glasses that contain water. These include obsidian, perlite, pitchstone, and hydrated volcanic ash or "pumicite" (Breese and Barker, 1993). Most obsidian contains from 0.1 wt.% to 1.0 wt.% total water bound as SiOH groups within the silica framework. This water is the original magmatic component present in the magma upon chilling. A few dense Recent glasses are hydrated beyond the obsidian stage, although older glasses extensively occur as perlite (2-5 wt.% water). Perlite thus is a hydrated volcanic glass formed through secondary alteration of obsidian by the incorporation of water into a glassy silica structure primarily during weathering. While several theories describing the timing and water sources of hydration have been proposed, the best explanation appears to be a slow post-emplacement hydration of the cooled glass by meteoric water. Although mechanisms such as hydration by magmatic or meteoric waters during or shortly after emplacement, or hydration by water exsolved during cooling may occur, their significance has not been demonstrated. Hydration of obsidian and the formation of perlite deposits is a gradual process of inward migration of meteoric water into the glass and incorporation into the glass structure as molecular water and SiOH groups.

Jezek and Noble (1978) described the process as associated with progressive incorporation of water and ion exchange. Friedman and Long (1976) showed that the composition of the glass phase and the temperature of the glass are important factors influencing the rate of hydration. The hydration rate slows down with decreasing temperature and increasing calcium and magnesium content. The rate increases with increasing silica content. The arcuate or concentric fractures that characterize dense onionskin perlite are the results of tensional strain associated with the hydration of glass and associated volume increase (Friedman and Smith, 1958; Jezek and Noble, 1978; Breese and Barker, 1993).

Volcanic glasses that have become perlite occur with rapidly quenched margins of silicic domes and lava flows with vitric or glassy tephra, and with glassy zones welded ash-flow tuffs. "Perlitized" glassy plugs, lacoliths, and dikes have been reported but are uncommon. Extrusion of viscous silica-rich lavas often produces steep-sided domes formed through the external distension and expansion of the lava mass as it accumulates above the vent. Peripheral flows covering several square miles or more are commonly associated with dome structures and complexes. The eruption of silicic lavas with lower emplacement viscosities has produced flow and dome-like complexes of even larger areal extent. Glass zones are frequently present on the domes and flows, marginal mantles and as associated tephra. Hydration occurrences can be important commercial sources of perlite.

A typical zonation found in many flows and domes consists of a texturally zoned exterior glass unit that encases interior, partly devitrified glasses and a felsite core (Figure 2). The concentric zonation is produced by rapid quenching of exterior surfaces and slower crystallization within the interior. The glass mantle can occur basal, marginal, and/or upper margin and can be tens of feet thick. Exterior glasses are typically pumiceous and encase denser obsidian. These grade into, and often interfinger with, more highly crystalline rocks of the interior core. Glass exposed to hydration processes, including those associated with vitric tephra, alters to perlite through the incorporation of water. Hydration and the resulting perlitic fractures are superimposed on the primary textures and zones of texture. Primary texture remains intact and is evident as the textural varieties of perlite that are described below.

Progressing toward the interior of the flows and domes, the textural subunits of the exterior glass mantle are distinguished as admixtures of pumiceous ("shardy") granular, and classical textural types. The textural types are recognized by the degree and distortion of primary

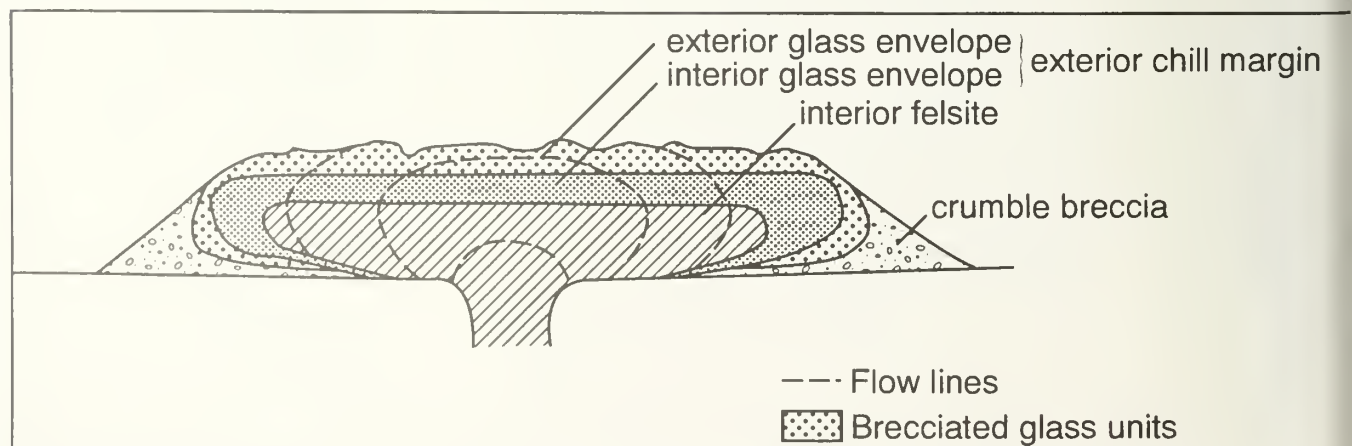


Figure 2. Schematic cross section of an endogenous perlite dome showing idealized lithologic zonation (after Whitson, 1982).



sirculation and by the presence of distinctive fracturing. These subunits are gradational in nature and are best cognized by the predominance of individual textural types. At the base of the exterior perlite mantle and below the zone of perlite that is commercially important, the hydration of obsidian to perlite is incomplete and the distinctive "marekanitic" zone is present, typified by numerous remnant obsidian nodules. These nodules, or "apache tears," occur as isolated or interlocking masses that form pods of varying dimensions. This unit extends from a gradational zone into the outer portion of the interior devitrified glass envelope, which in turn encases the crystalline, felsite core.

Common textures of perlite, as related to increasing density, are pumiceous, granular, and classical perlite. Pumiceous perlite is typically present at the margin of the deposit and is typified by frothy, open vesicles that can show flattening and distortion due to compression and bowage. Remnant obsidian cores and perlitic fractures, if present, are generally restricted to dense vesicle-wall junctions and may not be readily evident megascopically. This perlite is commonly friable and is mined with relative ease. Perlite with a granular texture is characterized by a jagged appearance and blocky fractures. Collapsed vesicles impart a silky luster to surfaces that are nearly parallel with flow foliation. Well-developed perlitic fracture and obsidian nodules are rarely observed in this type of perlite. As a denser textural variety, granular perlite typically mills well. Classical perlite has well-developed perlitic fracture and pearly-to-resinous luster; it is this textural variety that initially served as the basis for the definition of perlite. Viewed in thin section, this is the densest of the perlite types. Widely spaced vesicles are present, but are highly collapsed. Remnant obsidian nodules can be quite abundant and can occur as isolated grains or as pods of varying dimensions. The appearance of obsidian grains in the classical zone can be abrupt or gradational but can also increase rapidly toward the interior of the unit or laterally into subzones in which hydration of the glasses is incomplete.

## MINING AND MILLING OPERATIONS

Each commercial operation mines and processes perlite in a slightly different way. All mines except one are open pits. In some operations the ore is hard and must be drilled and blasted. In others, particularly larger operations, the ore breaks easily and can be extracted with scrapers. Some producers crush the ore at the mine while others have all crushing facilities at the mill. Most operations move crude perlite from the mine to the plant by truck, however, some mining operations are near enough to either dump ore from a scraper directly into the crusher or to use conveyor belt systems. At the mill perlite is

crushed, commonly to less than 6 inch, dried to remove free moisture (combined moisture is unaffected), crushed to -6 mesh, and screened to saleable sizes. All but one company produce more than one size of crude perlite. Oversized material is reground until it achieves proper size(s). Perlite is stored in storage tanks at the mill until it can be shipped to expanders. Some operations have expanders at or near the mill, but most move crude perlite to expanders located in various parts of the country (Figure 1, Table 1).

## DISTRIBUTION OF COMMERCIAL DEPOSITS

The following section on western commercial perlite is based on interviews with plant and mine managers and owners during February 1993, and on written material supplied by company personnel.

### ARIZONA

Middle Tertiary rhyolite lava flows cover low-lying hills on the northern flank of Picketpost Mountain and a few miles to the east. The occurrences are west and southwest of Superior in east-central Arizona, about 30 miles east of Phoenix (Figure 3; Welty and Spencer, 1987). Within the flow-banded rhyolites is a 6 to 50 foot-thick layer of perlite that locally exceeds 600 feet in total thickness (Welty and Spencer, 1987). Anderson and others (1956) described the perlite as containing 90% glass and 3.8 wt.% water, with plagioclase, K-feldspar, magnetite, and quartz cut by veinlets of cristobalite and pyrolusite. Chemically, the perlite is high in silica (>70 wt.%), low in iron, and contains less than 10 wt.% alkali elements.

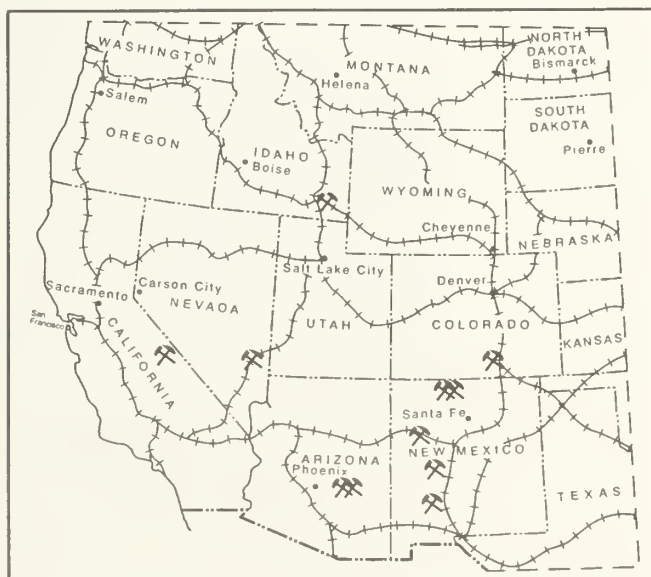


Figure 3. Index map of commercial perlite deposits in the western United States.

Table 2. Perlite mining operations in the United States.

State	Company	Type of Perlite	Mining Method
Arizona (Superior)	Harborlite	Classical	Ripping
	Nord Perlite	Mixed (granular and classical)	Mostly drill and blast
California (Big Pine)	American Perlite	Granular	Ripping
Colorado (Florence)	Persolite Perlite	Granular/breccia	Ripping
Idaho (Malad)	National Perlite Products	Granular	Ripping
Nevada (Caliente)	Wilkin Trucking & Mining	Classical	Drill and blast (underground mine)
New Mexico	Dicaperl <sup>1</sup> (Socorro)	Granular	Ripping
	Dicaperl <sup>1</sup> (No Agua)	Granular	Mostly ripping
	Harborlite <sup>2</sup> (No Agua)	Mixed (mostly granular and pumiceous)	Mostly ripping
	U.S. Gypsum (Grants)	Granular	Front-end loader

<sup>1</sup>Formerly Grefco<sup>2</sup>Formerly Celite, formerly Manville

Two companies, Harborlite Corporation and Nord Perlite, mine perlite near Picketpost Mountain in Pinal County (Table 2). Ore is crushed, dried, and sized in two screening plants on the same rail spur. Neither plant has an expander, so crude perlite is expanded elsewhere, primarily for use as filter aid.

### Harborlite Corporation (Superior)

The perlite deposit acquired in 1960 is mined by Harborlite to the southwest of Superior, Arizona, from one of two pits. These are about 2 miles east of the plant and east of US-60 past the Solid Waste Transport Station, across Queen Creek and to the right. The lower (inactive) pit has four 12-foot benches, covers 10-15 acres, and has a little rhyolite and some obsidian. The upper (active) pit has three 12 foot benches, covers 5-10 acres, and has 20-30% rhyolite. The onionskin perlite mined in both pits contains both black "Apache tears" and patches of obsidian that expand well enough to make it better perlite ore than the local granular perlite. Rapid lateral changes in the ore body complicate grade control. Perlite is drilled and blastholes are loaded with dynamite and ANFO (if dry) or unigel (if wet). Loose perlite is stockpiled centrally with a Caterpillar 980C front-end loader (Photo 1) serving two 10-wheel dump trucks (Photo 2) that deliver to

the plant just south of the Nord Perlite Plant. Some sorting of waste from perlite is possible in the pit, but only when the waste is in large masses.

At the plant (Sec. 9 T2S R12E), crude perlite is dumped by Caterpillar 980C front-end loader onto a 6-inch grizzly. Sledge hammers are used to break oversized material through the grizzly to the jaw crusher that reduces the perlite to 1/2 inch. Crude perlite is stored in a 500-ton tank by the rail siding before it is dropped by gravity into the covered railcars (Photo 3).

Crushed and dried crude perlite (-30 mesh) is shipped to company expansion plants in California, Florida, Michigan, and Wyoming, and to non-company plants in California, Florida, Louisiana, and rarely Texas (Table 3). Perlite expanded at Harborlite plants is used in filter aid (80%) and in insulation. The mine at the plant produce about 35,000 to 40,000 tons of crude perlite per year with nine employees; 2 managers, 1 maintenance supervisor, 1 secretary, and 5 hourly employees.

### Nord Perlite

The Nord Perlite mine and crushing plant, acquired in 1986, are near Superior, Arizona (Figure 3). The mine operated about two-thirds of the time and consists of two pits about 3 miles southeast of the plant and about 0.5 mile southeast the Harborlite mine. It is 2.4 miles from US-60 via Mary Road in Superior. Proceed across Queen Creek and along powerlines, that are crossed several times before the pit, and turn right at the ballpark. Proceed to the end of the pavement and then right on dirt road to the pit in a canyon. Nord holds five patented claims and numerous unpatented claims on Bureau of Land Management (BLM) land. The perlite (Photo 4) consisting of intimately mixed onionskin (50%), granular (50%), and pumiceous varieties (trace), must be drilled and blasted with ANFO about 75% of the time (Table 2). A D9H Caterpillar bulldozer rips the remaining 25% of unblasted perlite. The perlite contains some obsidian, but most of the obsidian expands with the perlite and is not a problem. A Caterpillar 966D front-end loader serves two dump trucks (10-wheel) moving perlite to the plant (Photo 5).





Photo 1. Caterpillar 980C front-end loader mining loosen onionskin perlite at the upper pit of Harborlite Perlite southwest of Superior, Arizona.



Photo 2. Harborlite front-end loader loading perlite into 10-wheel dump trucks at the mine near Superior, Arizona.





Photo 3. Storage and loading facilities for 100 st railcars at the Harborlite Perlite screening plant southwest of Superior, Arizona.



Photo 4. Mixed onionskin, granular, and pumiceous perlite mined at the Nord Perlite mine south of Superior, Arizona.



Photo 5. Nord's dump trucks deliver perlite ore to the crushing facilities at the screening plant southwest of Superior, Arizona. Various types of perlite are stored near the plant for blending to achieve uniform specifications.

Table 3. Perlite processing plants associated with mines in the United States.

State	(Location) Company Name	Local Company Expander	Volume Shipped (s) or Produced (p)	States Receiving Perlite Products
Arizona	(Superior) Harborlite Corp.	No	35-40,000 st/yr (s) -crude only-	CA, FL, LA, MI, TX, WY
	Nord Perlite	No	30,000 st/yr (p) -crude only-	IL, LA, PA, NC, TX
California	(Big Pine) American Perlite	No	50,000 st/yr (p) -crude only-	AZ, CA, FL, OR, UT
Colorado	(Florence) Persolite Perlite	Yes	2,000 st/yr (used <sup>1</sup> ) 5 st expanded -crude and expanded-	CO, WY, MT, ND, SD
Idaho	(Malad) National Perlite Products	Yes	100,000 4 ft <sup>3</sup> bags/yr (s) -expanded only <sup>2</sup> -	AR, CA, CO, FL, ID, IL, MT, NV, OH, OR, PA, TX, UT, WA, WI, WY, and Canada (Alberta and Manitoba), Taiwan, Korea, and Mexico
Nevada	(Caliente) Wilkin Trucking and Mining OR, UT	Yes	3900 st/yr (p)  -crude and expanded-	CA, FL, HI,
New Mexico	Dicaperl (Socorro)	No	25 railcars/wk 1-2 PD <sup>3</sup> railcars/wk -crude only-	AL, AZ, CA, CO, FL, GA, IL, IN, IA, KY, MI, NM, OK, PA, TN, TX, WI, and Canada and Mexico
	Dicaperl (No Agua-Antonito)	Yes	50-60 railcars/wk 1-2 PD railcars/wk 1-2 railcars/wk (exp <sup>4</sup> ) (s) -crude and expanded-	CA, CO, CT, FL, ID, IL, IN, KS, MA, ME, MO, MT, NM, NY, NC, OH, OR, PA, TN, TX, WA, WI, Mexico and Ontario, Canada
	Harborlite Corp. (No Agua-Antonito)	No	30 railcars/week 1-2 PD railcars/wk (s) -crude only-	CA, FL, IL, MS, PA, MN, TX
	U.S. Gypsum (Grants)	No	<1 railcar/week (s) -crude only-	IN, MO, NY, OH, TX

Note: Volume figures are supplied by the companies and are not consistent. For estimating stpy from railcars/week, 1 railcar/week is about 5000 stpy.

Persolite uses perlite purchased from Dicaperl to augment their own production of crude.

Mine will re-open summer 1993 or 1994 and crude shipments will resume.

<sup>3</sup>Pressure-differential (PD) - railcars using pressure differences to unload fine-particle perlite.

<sup>4</sup>Expanded perlite, bagged or in bulk.



Photo 6. Primary jaw crusher at Nord Perlite plant near Superior, Arizona (reverse side of Photo 8). Perlite is dumped in at top (left of worker), crushed, and moved by conveyor belt to covered storage area to the right.

At the Nord plant, perlite is passed over a grizzly (-6 inch). Sledge hammers are used to reduce +6 inch perlite to pass through the grizzly and into a jaw crusher. The jaw crusher (Photo 6) reduces the perlite to -1.5 inch before it is passed through a roll crusher and then a rotating tunnel dryer. After drying, the perlite product is -34 mesh. The +34 mesh material goes through a turbo impact crusher in a closed-circuit system to obtain -34 mesh material. The -34 mesh perlite contains 6.5 to 8.5 wt.% total moisture and 1.5 to 3 wt.% combined moisture. Sized perlite is stored in four storage tanks ready to be gravity-fed into railcars for shipment to expansion plants to make filter aids (Photo 7). Fines removed by dust collectors from crushers and conveyers are stored on site to be dumped and then covered in an area west of the plant.

About two-thirds of the perlite is shipped from Superior to Nord expansion plants in Fort Worth, Texas, and Harrisburg, Pennsylvania (Table 3). About 95% of the perlite is shipped by rail in 100 st bottom-dump railcars. Railcars are moved by Magma Copper switch engines along the Magma spur 24.5 miles to Magma Junction at Florence, Arizona, on the Southern Pacific Railroad. The remaining 5% of perlite goes to plants in 24 st trucks with low-cost backhauls that undercut railroad rates or meet unexpected shortages. Nord perlite is expanded for filter aids owing to its ease of shattering, although it can make horticultural or construction grades if necessary. The Nord mine and plant employ nine hourly employees plus a manager. The mine produces about 30,000 short tons of perlite per year (stpy).



Photo 7. Storage piles (right), tanks for storage of various size perlite (center), and loading facilities (left) at the Nord Perlite operation at Superior, Arizona. Note the boom from the storage tanks for loading 100 st railcars. The car at the left is a pressure-differential (PD) type for moving small-size crude perlite.

## CALIFORNIA

### American Perlite

The Fish Springs perlite area is in western Inyo County, about 7 miles south of Big Pine (Figure 3). Recent volcanic dome, which rises as a conspicuous about 200 feet high, is surrounded by outwash gravel debris derived from the east face of the nearby Sierra Nevada (Chesterman, 1957). The dome is elongated east-west and capped by pumiceous perlite that grades downward into less pumiceous perlite. The zone of noble perlite is about 80 feet thick and is underlain successively by brecciated obsidian in a pumiceous perlite matrix and a dense glassy perlite-vitrophyre. Perlite ore is light-gray to white, medium- to fine-grained, pumiceous and locally contains small, rounded, dark-gray to black obsidian.

The American Perlite quarry and plant are west of US-395 and about 10 miles southwest of Big Pine, California (NW 1/4 Sec. 30 T10S R34E; Figure 3). The operation is reached via the Fish Hatchery Road, either by the north or south exit, through Tinemaha Creek Campground then north to the mine and mill at the base of the perlite deposit.

The perlite mine came on stream in the early 1950s and was purchased in the early 1960s by the Duncan family as Redco, Inc. American Perlite was incorporated in the mid 1980s and operates the perlite mine. The 150-foot by 200-foot open pit in layered, vesicular, pumiceous perlite is on the south-western side of a hill above the plant and is physiographically part of the east flank of the Sierra Nevada. The perlite contains no obsidian and few other impurities. Older perlite pits are common in the vicinity of the active one. The perlite is exposed in a 1-mile by 0.75-mile series of knobs partly buried by detritus from higher mountains to the west.

Layered perlite is ripped with a 1 1/2-ton Caterpillar pushed by a D6 Caterpillar and is moved by Caterpillar 950 and 980 front-end loaders to a grizzly above the plant (Table 2). Crude perlite passing the grizzly is dropped through a jaw crusher and screens onto belts that lead to a 3-foot cone crusher (-5/8 inch output) and through a tunnel dryer fueled by diesel (Photo 8). A roll crusher is being tested and will soon be brought on line. After drying to about 4% total moisture, a roll crusher and horizontal hammermill further reduce the perlite to -1/8 inch. Screens are employed to separate the perlite into -1/8, +1/16 inch; -1/16, +1/32 inch



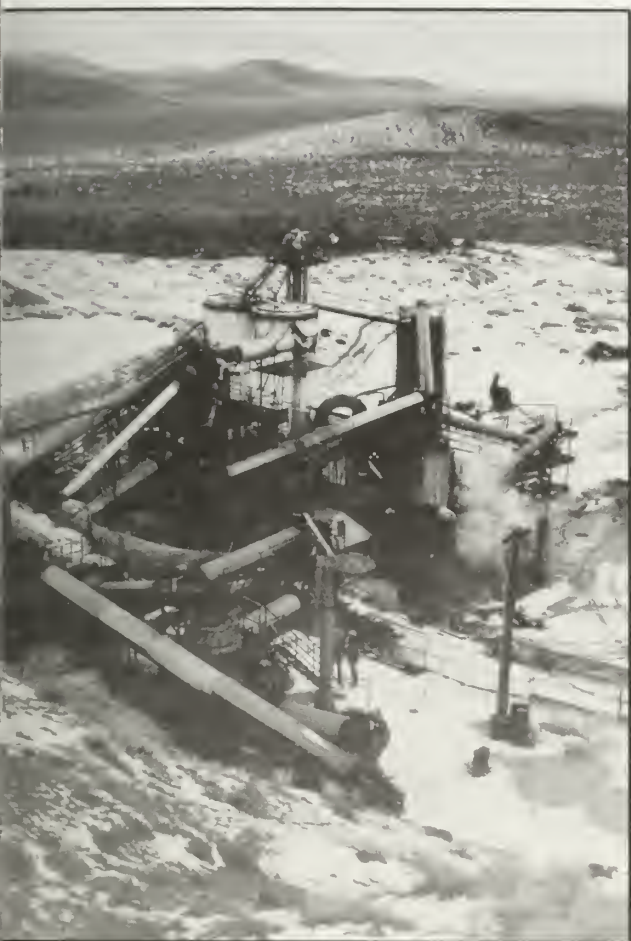


Photo 8. Crushing, storage, and loadout facilities at the American Perlite plant south of Big Pine, California. The picture, taken during February 1993, shows snow at this elevation of the east slope of the Sierra Nevada.

1/32 inch, +400 mesh; and -400 mesh sizes. The finest size fraction from the baghouse, about 4% of the total, is not marketed and is buried. The other three fractions are the principal perlite sizes, although the -1/8, +1/16-inch and the -1/32, +400 mesh sizes are each blended with the -1/8, +1/32-inch fraction to produce two additional sizes. A 30 short-ton (st) Euclid dump truck is used to move perlite around the plant area. The main products are horticultural- and construction-grade perlite. Seven bins and four additional tanks in a bunker house store the sized perlite on site. Nine employees at the mine and plant work five 8-hour days per week with a swing shift utilized as needed to meet surges in demand such as for horticultural grade in the spring. The plant processes about 25 to 30 st/hr in summer and about 20 st/hr in winter for about 10,000 short tons per year (stpy) production.

The perlite is trucked, usually by Lone Pine Trucking, to customers in California (Los Angeles, San Diego, and occasionally San Francisco), Phoenix, Arizona, Salt Lake City, Utah, and occasionally Portland, Oregon (Table 3). Lone Pine Trucking has five bottom-dump and two trans-

fer trucks. American Perlite may use the proposed railhead in Owens Lake, about 60 miles to the south. They have not shipped by rail since the railhead at Minah, Nevada, was closed. Most of the perlite is shipped to the Redco II expansion plant at North Hollywood, California, about 350 miles to the south.

## COLORADO

### Persolite

The Rosita Hills deposit, 0.5 to 2 miles south and southwest of Rosita, Colorado (Secs. 32 and 33, T22S, R71W and Secs. 5 and 6, T23S, R71W) is at an altitude of 8700 feet (Bush, 1951). Persolite's mine is on 23 unpatented claims covering a small reserve base of unknown tonnage. The perlite crops out along gentle lower slopes of the Rosita Hills over about 1 square mile. It is a nearly horizontal flow 40-75 feet thick, overlain and underlain by pumiceous material. The Rosita deposit is difficult to mine because the ore is easily pulverized into very fine material (Table 2). Two perlite phases are present, a light greenish-gray type with orbicular to acicular fracture and a harder, dark-gray perlite with irregular fracture. A dark obsidian layer is commonly present at the base of the main perlite flow.

The perlite expansion plant of Persolite Products Inc. is in Florence, Colorado, just south of US-50 on CO-67, about 35 miles north of the Rosita Mine. The facility is in a three-story concrete building with a very large cement smoke stack on the left (east), just before crossing the railroad. Persolite is run by the Steiner family and employs six people on a five-day, 10- or 11-hour schedule.

The perlite is difficult to expand, even though it contains about 3.5% combined water. Expansion occurs at relatively high temperatures, even after reaching 600°F in a rotating horizontal preheater (Photo 9). Obsidian is absent, but iron and rhyolite impurities are present. The expanded perlite is off-white (slightly grayish), even if

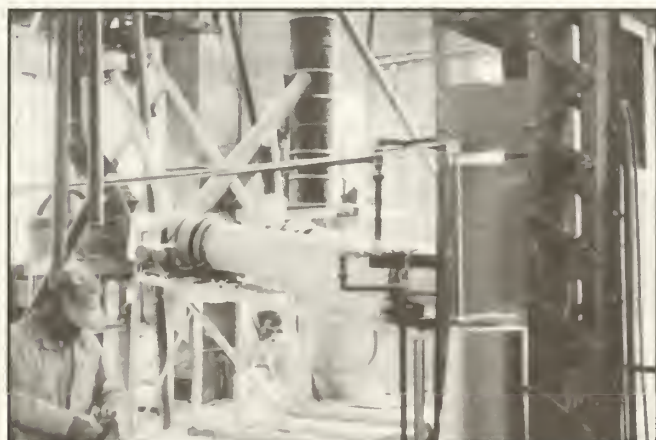


Photo 9. The preheater (nearly horizontal tube near the center) at the Persolite Perlite expander at Florence, Colorado.

iron is low, and is best used--at about 7.5 pounds per cubic foot (lbs/ft<sup>3</sup>)--for lightweight aggregate.

Persolite buys more than 95% of their crude perlite from Dicaparl (formerly Grefco) at Antonito, Colorado. The Dicaparl crude perlite needs no preheating if fine and is preheated to 225°F if it is coarse. Owing to short retention time, coarser fractions expand poorly in the two 18-inch Stein and Murdoch US225 vertical furnaces now in use. The furnaces and preheaters are fired by natural gas. The crude from Dicaparl reaches Florence by rail in 100 st bottom-drop hopper cars, is dropped at the siding on the south edge of the plant, loaded into trucks using conveyor belt loader, and hauled directly to the nearby expansion plant without further processing. The Dicaparl grades used are 76S (0% +8 mesh and 85-90% +12 mesh) and 77 (18-20% +8 mesh and 90% +12 mesh). The less than 5% crude perlite from the Rosita Mine is mined in summer campaigns. It is stockpiled on a pad about 0.25 mile southwest of the expansion plant in Florence. The mine-run Rosita perlite is crushed on the pad using a jaw crusher and two roll crushers prior to drying. Capacity of this plant is about 4 tons/hour. The processed crude perlite is blended at the expansion plant to achieve constant quality.

The Rosita deposit was originally opened around 1948 by the Alexander Film Company. It was purchased by Great Lakes Carbon in 1954 or 1955. Grefco (the successor to Great Lakes Carbon) sold it to a Mr. Freudenburg, a Boulder, Colorado, businessman, who formed Persolite around 1958. Beginning in the early 1980s, the Rosita deposit was used less and less, as the need for lightweight roofing decks, the original primary product, decreased.

The two principal Persolite products presently are masonry fill (about 50% of sales) and horticultural perlite (about 50%), with minor sales of plaster and concrete aggregate. The main Persolite markets are in Colorado and Wyoming, with lesser amounts in Montana, North Dakota and South Dakota (Table 3). Persolite markets perlite without a sales force, except for using a technical representative for masonry fill. They rely on long-term customers, primarily distributors, for repeat orders. These distributors do have technical representatives to service their customers using Persolite products. Substitutes such as vermiculite, rigid styrofoam, and scrap styrofoam beads offer competition. Overall, the horticultural market is stable, while markets for masonry fill, texturing, and lightweight aggregate for roof decks are declining. Persolite is not planning to increase capacity.

The expanded density of masonry fill is about 5.25 lbs/ft<sup>3</sup> and horticulture perlite is about 5.5 lbs/ft<sup>3</sup> in paper bags that top out at 4 ft<sup>3</sup>. Bagging capacity is about 70 bags per hour for coarse-size perlites and up to 80 bags per



Photo 10. Bagging facilities at the Persolite operation. Bags, filled with perlite, are pallerized (right) for shipment from Florence, Colorado, to horticultural-grade perlite distributors in Colorado and nearby states.

hour for fine-size perlites (Photo 10). Testing is limited to sieving, owing to the broad specifications for perlite, except for occasionally made special products.

## IDAHO

### National Perlite Products Company

National Perlite Products Company (NPP), a division of Oglebay Norton Company (ONCO), operates an expansion plant at Malad, Idaho, and a perlite mine and mill on a 7,000-acre property about 25 miles north of Malad. The mine is in Oneida County and is surrounded by the Caribou National Forest near the headwaters of Writ Creek. ONCO acquired the mine and mill in December 1986 from the Paul Mills family, who had developed the operation as Oneida Perlite in 1959-60 and marketed only bagged expanded perlite products until the operation was sold. NPP improved the facilities and sold products throughout the United States. A grain elevator on the Union Pacific Railroad at Malad was purchased and modified to a rail loadout facility.

Perlite, pumice, and other rhyolite rocks in the Malad area appear to be part of a collapsed dome or caldera. The NP-1 open pit was used from 1987 until 1992 (Sec. 2).





Photo 11. National Perlite Products crushing and screening operation near their perlite mine north of Malad, Idaho.

1S, R35E). The mill is scheduled to reopen in the fall of 1994 using crude perlite from the new NP-2 pit (Sec. 26, 1S, R35E) that will produce coarser grades of perlite and less dust. In the area of the present NP-1 pit, a dacite dike underlying the perlite has produced nearly vertical dykes on multiple perlite flows. Perlite in the NP-2 and NP-1 pits is essentially free of clay, obsidian, and rhyolite, and has only 0.1 to 0.2 wt.% silica as quartz, a little manganese oxide, and up to 10 wt.% free moisture. Free silica is not present in detectable amounts in the expanded perlite products.

The perlite is ripped with a D-9 Caterpillar tractor and moved by 10 flatbed trucks to the crushing-screening-milling facility near the mine (Photo 11). It is crushed by jaw and vertical impact crushers to -6 mesh (Table 2). A propane-heated dryer reduces the free moisture in the perlite to less than 1 wt.% before it is screened and stored in one of six on-site storage silos. As needed, the coarse product can go through a hammer mill for further size reduction before storage. Mining and milling operations cease in the winter owing to heavy snowfall.

Sized perlite is moved from the silos by bottom-dump tractor-trailer highway trucks to Malad and stored in silos ready for expansion at the plant or stored at the railroad siding on the south side of Malad to await transport to other expanders. The NPP expanding plant is close to I-80 on the northwest side of town and one block east of Main Street (Photo 12).

The Stein and Murdoch Model 225 (18 inch, 1 short ton per hour [stph] rating) vertical expansion furnace is fueled by propane and typically produces one bag of expanded perlite per minute with variation due to crude-perlite size (finer is faster) and the ambient temperature. Sized perlite feed is preheated as it descends from the storage bins to prevent shattering during expansion. The expanded perlite passes through cyclones which classify it for the bagging line or for cryogenic or fines bulk storage. Dust collection at the plant and railroad siding is done at all necessary points in the process.

The mine and mill were closed--after perlite products were stockpiled in Malad--in October 1991 to address dust problems associated with the mill crushing, screen-





Photo 12. Mill at the National Perlite Products operation in Malad, Idaho. The dark-colored vertical expander projects through the roof of the building at the left. The light-colored tanks (near center) are for storage of several sizes of crude (unexpanded) perlite.

ing, and drying of perlite. At the peak of operations prior to closure, 31 people were employed at the mine, mill and plant, but this has been reduced to five or six who work four 10-hour shifts per week until operations resume at the mill, now scheduled for the fall of 1994 after the installation of a dust-control system and permitting. The perlite ore product stockpile has been replenished for the expanding plant, via rail and truck, using Dicaperl perlite ore products from Antonito, Colorado.

Since the mine and mill were put on standby, crude-perlite sales ceased while expanded perlite sales continued. Sales are typically 70% insulation, 25% horticultural, and 5% cryogenic. NPP is able to blend six basic perlite grades into a large number of customer-tailored products. The flexibility is aided by six storage bins at the mine, six at the plant, and eight at the railhead. The main crude-perlite size grades are: NP 110 Horticultural, NP

130 Horticultural (blend of 100 and 150), NP 150 Insulation, NP 190 Light weight concrete, NP 230 Cryogenic, and NP 270 Cryogenic.

A field sales force is not used and marketing is done by telephone or in person at the plant and through attendance at trade shows. Distributors are rarely used, but this is evaluated for each region. Crude perlite is shipped primarily in 100 st hopper cars or trucks to customers in California, Illinois, Wisconsin, Pennsylvania, Florida, Texas, Ohio, Arkansas, and Massachusetts (Table 3). Exports have gone to Canada, Taiwan, Korea, and Mexico. Output was 5-7 railcars per week prior to the temporary mine-mill closure. Expanded perlite, in 4 ft<sup>3</sup> paper or plastic bags (polyethylene, 4.5 mil) and 40 ft<sup>3</sup> supersacks, is shipped primarily by trucks (van or flat bed) to customers in Montana, Washington, Oregon, Idaho, Utah, Colorado, Nevada, and Wyoming.

NPP arranges shipping about 65% of the time, with customers supplying their own trucks the remaining 35%. Expanded perlite sales were about 100,000 bags in 1992, which equates to 1350 st with a typical bag weight of 27 lbs. Output is typically 15 pallets of 34 bags each (total of 510 bags) when the plant is operating all day. The plant furnace capacity is 3,000 stpy and the annual milling capacity is about 50,000 st of all perlite grades.

The reopened mine will supply superior crude perlite to their Malad expanding plant and ore product customers in the United States and Pacific Rim markets. The sales of perlite ore products to distant markets such as Florida show that they successfully compete in certain eastern markets against both other domestic and foreign producers.

## NEVADA

### Wilkin Mining and Trucking Company

The Wilkin Mining and Trucking operation in south-eastern Nevada uses classical perlite mined underground rather than granular perlite from an open pit. The Mackie perlite mine-- sometimes referred to as the Delamar perlite mine--is on the east flank of the Pahroc Mountains about 30 miles west of Caliente, Nevada (Sec. 34, unsurveyed] T4S, R62E; Figure 3). It is about 5 miles south of the highway on a dirt road just east of Pahroc Summit. Perlite has been mined there since about 1951, and the property was originally leased from A. J. Mackie. Producing claims presently are in two groups, one owned by Paramount Perlite and the other owned by the Wilkin family. Extensive underground workings are on the property about 1,000 feet southwest and above the present portal that was opened about 3 years ago. At present, crude perlite is produced at about 4,000 short tons per year. Wilkin supplies both crude and expanded perlite to Paramount Perlite at Paramount, California, and also sells expanded perlite under their own brand name.



Photo 13. Portal of the underground Wilkin Trucking and Mining Mackie perlite mine 30 miles west of Caliente, Nevada. The ore is a bluish-gray onionskin perlite.

Mining activities at the portal of the present Mackie mine exposed gray/blue perlite (Photo 13). Near the top of the mined interval are red, black, and brown streaks of perlite and obsidian (up to about 1 inch) occurring in regular patches (Photo 14). An outcrop of layered onionskin perlite about 30 feet thick dips about 15° to the north and appears to be the glassy portion of a vitrophyre. Reddish and gray rhyolitic breccia with scattered perlite fragments caps the sequence and extends at least several hundred feet beyond the exposed perlite. The active workings extend about 100 feet and have a good back, so no roof bolts or timbers are required.



Photo 14. Streaks of red obsidian and vitrophyre (black) in bluish-gray perlite (gray) above the mined perlite interval at the Mackie Mine.

Campaign mining is by room-and-pillar and drilling-and-blasting (Table 2). Blast holes are dug with an Atlas-Copco sinking hammer because the perlite is soft (compared to ordinary rock) and plugs the steel during jackleg operation. A typical blast hole round is 10 feet by 12 feet by 6 feet deep and charged with blasting gel in 12 holes. ANFO is occasionally used to take up the bottom. About 1-2 rounds can be made during a 8 hour day by a crew of two miners. Shot muck is moved to an underground storage area by a small, rubber-tire front-end loader (Caterpillar 920). A small, tracked loader (Caterpillar 933) is used principally to trim the walls and back, and is used in areas that are too tight for the rubber-tire loader to work. The underground storage is preferred to maintain uniform moisture content in the perlite. On demand, the rubber-tire loader moves the perlite to either a 10-wheel dump truck or an end-dump tractor-trailer for the 30 mile haul to milling facilities in Caliente.

A small, open area 200 feet east and downhill from the portal has been cleared of overburden and will be the site of a future portal. A small pit dug by a Koehring 466D shovel exposed the faulted east boundary of the deposit. No solid perlite is found east of the fault.

The crusher is on a railroad spur in northeast Caliente, just east of Meadow Valley Wash. The crude perlite is crushed to -5/16 inch before it is moved about 0.5 mile to the expansion plant west of US-93 in a small canyon at the northwest edge of Caliente. A new crushing facility is under construction at the expansion plant and should be operational in 1994. Some crude perlite is stored both at the crushing facility and at the expansion plant. At the expansion facility, a front-end loader moves the perlite into a hopper from which it is elevated to screens and separated into four sizes before being processed through the plant. The perlite is fed into a 200°F (upper end) to



1200°F (lower end) preheater and dryer that removes some free moisture using heat that would otherwise be wasted in the hot exhaust gases from the furnace. The propane-fired, horizontal furnace was custom-designed by the owners and continues to evolve in order to maximize the yield of this particular ore. Expanded perlite is blown onto a jig where waste material, or partly expanded perlite and obsidian, falls out. Expanded perlite is elevated and passed over screens that separate it into four sizes: the smallest product is  $-1/16$  inch (No. 1) and is used as a soil additive or quick-set plaster additive;  $+1/16 - 5/16$  inch (No. 2) is the most popular horticultural grade;  $+5/16 - 1/2$  inch (No. 3) is for horticultural applications requiring more aeration or drainage; and  $+1/2$  inch (No. 4) is used mostly for orchid propagation.

Size of the finished product is mostly determined by closely controlling the feed size; however, any material that is too coarse is reduced with rolls in order to meet a required size. The expanded product is packaged in either 4 ft<sup>3</sup> paper bags or 6 ft<sup>3</sup> reusable fabric bags for shipment. Usual production is 16-20 bags per hour depending on bag size and product density required (up to 450 bags per day) that are placed on pallets for shipment. Transport is

by truck only, although the plant is on the railroad, about 65-75% crude and 25-35% expanded. Expanded perlite is shipped in bags labeled "SpongeRok" (Photo 15) either to the Paramount distributing facilities or directly to their customers principally in California but occasionally in Florida and Hawaii (Table 3). Bags labeled "Pal Giant Exxpanded Perlite" are distributed by Wilkin principally to northern and central California but also to adjacent states. Paramount Perlite markets 90-95% total Wilkin production.

Crushed and screened crude perlite was moved exclusively by rail in covered hopper cars for many years. For several years, truck transport by bottom-dump tractor-trailer trucks has been the only means of transporting this ore about 400 miles to the Paramount expansion plant. Both economic and service factors are given considerations in moving crude perlite by truck. Most of the expanded perlite from Paramount and Wilkin is used for horticulture.

## NEW MEXICO

Three companies operate four mines in New Mexico (Figure 3). The companies include: Dicaperl Perlite, perlite unit of Grefco, which has mines in the No Agua Peaks area of Taos County, north-central New Mexico and near Socorro, Socorro County, central New Mexico; Harborlite, which operates the former Manville or Cement mine in the No Agua Peaks of north-central New Mexico and U.S. Gypsum northeast of Grants, which mines perlite in west-central New Mexico.

### Dicaperl Perlite (No Agua Peaks and Antonio)

The No Agua Peaks are composed of late Tertiary extrusive rhyolitic rocks dated at 4.2 million years (Whitson, 1982). They cover an area of about 4 square miles and consist of four prominent peaks that represent the erosional remnants of two rhyolitic domes and large



Photo 15. SpongeRok expanded perlite in 4 ft<sup>3</sup> paper bags on pallets in Caliente, Nevada, ready for shipment to California markets.



Photo 16. The No Agua Peaks in north-central New Mexico (picture taken from the southwest) are the world's largest known concentration of perlite. The West Hill (center) and South Hill (right) and the west flank of the west hill (left of center) are the mining areas in 1990. The eastern flank of San Antonio Mountain is at the extreme left.



prominent hills and ridges. The low hill-and-ridge area to the southwest of the four peaks and consists of several rhyolitic flows derived from the lower flanks of the prominent westernmost peak (Photo 16).

General Refractories Company started mining at No Agua Peaks in 1958. The mine is now on patented claims and other fee lands comprising 1200 acres. The company, which later changed its name to Grefco, opened the El Grande Mine (Sec. 15, T29N, R9E) on the southwest flank of the four No Agua Peaks (Photo 17). Grefco recently signed perlite mining and milling to a subsidiary known as Dicaperl Perlite. The mine at No Agua has a very large reserve of dominantly granular perlite with some pumiceous perlite at the east edge of the property which forms the boundary with Harborlite. Obsidian, generally less than 3 wt.% bound water and dispersed by blending at the stockpile, is principally on the north side of the main pit vertical patches.

At present, the surface has been lowered about 150 ft in the approximately 400 acres that encompass the mining area. Parts of the main pit have only 7 to 10 feet of good ore remaining, but other areas have at least 150 feet left to mine. Although most mining requires only that the ore be ripped with a Caterpillar D8L tractor (Photo 18), twice in the last three years the perlite on the south edge of the pit was blasted with ANFO (Table 2). Two Caterpillar 631 scrapers (pushed with the D8L although they can scrape the ore alone) pick up and move the ore to the screening plant near US-285 on the west side of the property (Photo 19). Three people are employed in the mine.

Scrapers deliver crude perlite to a grizzly (+14 inch) and crush oversize as they pass over it. The primary jaw crusher below the grizzly reduces the perlite to about -2 inch. A conveyor belt moves the ore to a hopper before being drawn out to two inclined rotary dryers (8 feet by 45 feet and 6 feet by 45 feet). The dryers, fueled with No. 6 fuel oil and reclaimed oil, reduce 40 st/hr ore from about 12 wt.% (winter) or 6 wt.% (summer) free moisture to less than 0.5 wt.% at a maximum temperature of 225°F. The dried perlite is screened and the +6 mesh is re-ground in a turbocrusher. The -6 mesh is screened to seven fractions (ranging from 8 mesh to 200 mesh) and conveyed to seven 100 st storage tanks. Perlite can be ground to meet surges in demand for a particular size, blended to about 30 standard sizes, or custom-blended. The screening plant produces about 200,000 st/yr of perlite and employs 24 people.

Two-to-three bottom-dump trucks are under contract to move the perlite from the screening plant at No Agua 25 miles north to the railhead and expansion plant south of Antonito, Colorado. The ore is dumped and moved by conveyor belt and elevators to one of 10 storage



Photo 17. The Dicaperl perlite mine on the western flank of the West Hill at No Agua Peaks. San Antonio Mountain rises in the background.



Photo 18. Ripper (right) and scraper (left) in the Dicaperl mine at No Agua Peaks, New Mexico.



Photo 19. Dicaperl crushing and screening plant west of the No Agua Peaks in northern New Mexico in March 1993. Scrapers move the ore from pit on top of the west flank of the peaks beyond the background down to the unloading facilities at the left side of the plant.

bins at the Antonito facility. Nine bins hold 100 st each and the tenth holds 2,000 st. Most (88%) perlite is loaded into railcars for shipment to expanders in other states; 7% is expanded on site. The majority are 100 st bottom-dump railcars, but some (1 to 2 cars per week) are leased 100 st pressure-differential (PD) railcars for fine-grained perlite. About 5% of crude perlite is shipped in 30 st trucks to customers, commonly in the customer's trucks or contract carriers. Nineteen people work at the Antonito expansion plant.

Dicaperl ships about 20% of their crude product to company-owned Chemrock Corporation plants in Florida, Indiana, Maine, and Tennessee. About 80% of the product goes to outside customers in Florida, Idaho, Illinois, Indiana, Maine, Massachusetts, Missouri, North Carolina, Ohio, Oregon, Pennsylvania, Tennessee, Texas, and Wisconsin (Table 3). About 50 to 60 railcars of crude perlite are shipped from Antonito each week.

The Antonito, Colorado facility includes two vertical expanders (18.5 inch and 30 inch diameters) that are operated on the second and swing shifts. The first or day shift is used to do maintenance and to load railcars and trucks. Expanded perlite is bagged and shipped to California, Connecticut, Idaho, Kansas, Montana, New Mexico, New York, North Carolina, Oregon, Texas, Washington, Canada (Ontario), and Mexico. The expanded perlite is shipped mainly by truck in 25 lb, 20 lb, and 18-20 lb paper bags (2-ply, Kraft). Trade names of expanded perlite bagged at Antonito are "Dicaperl" for horticultural or fillers in 4 ft<sup>3</sup> bags and "Dicalite" in smaller bags by weight for filter aid. About one railcar of expanded perlite is shipped from Antonito each week.

About 50% of Dicaperl perlite is used in acoustical ceiling tile, 32% as block fill and other aggregates, 10% as horticultural perlite, and about 8% as filter aid. Perlite filter aids are losing ground to diatomaceous earth. Microspheres of expanded perlite is a very small but growing market.

### Dicaperl Perlite (Socorro)

Older, more mafic volcanic rocks on the south flank of the Socorro Mountains southwest of Socorro, New Mexico, are overlain by a 7.8 million year high-potassium, high-silica rhyolite termed the Grassy Dome (Chamberlin, 1980; Bobrow and others, 1981). The rock is gray to buff and the texture is glassy to perlite. The perlite ore is the granular variety (Photo 20).

The Dicaperl Socorro mine and screening plant (T3S, R1W) employs 30. The mine is adjacent to the screening plant and occupies 70 to 90 acres on patented claim (Photo 21). The Socorro mine was one of the first perlite mines in the United States when it opened in 1949. It closed from 1959 to 1975, but a drill-hole intercept over 600 feet suggests very large reserves.

A mining crew of three works from about 6 a.m. to noon to replenish the surge pile and then finishes the shift doing reclamation work. The ore is ripped with a Caterpillar tractor and two scrapers move it to the primary crusher near the bottom of the pit (Table 2). The scrapers are Caterpillar 631B and 631D with a scraper auger for large or hard perlite. A grizzly passes -12 in perlite to the primary jaw crusher (-2 inch). A conveyor belt takes the perlite to a seven-day surge pile near the plant. A vibratory feeder below the surge pile moves ore into the plant where it is screened to -3/8 in. The +3/8 inch ore is recycled to a vertical impact crusher.



Photo 20. Fractured granular perlite exposed in the Dicaperl mine near Socorro, New Mexico.





Photo 21. Multiple mined levels in the Dicaperl mine near Socorro, New Mexico. Scrappers (lower left) move the ore from the pits to the primary jaw crusher (out of sight in a slot in the center-left) where it is crushed and then moved by conveyor belt to the left. The picture was taken to the southeast across the Rio Grande Valley (in background).

and then over the 3/8 inch screen. The crushed perlite is dried in a 400°F rotary dryer that reduces the free moisture to 0.25%. Discharged perlite has a temperature of about 250°F. The dryer is fired with waste crankcase oil purchased in Albuquerque about 75 miles to the north.

About 130,000 st of crude perlite of all sizes were sold in 1992. Addition of regrind circuits has added capability to match better surges in demand for a particular grade. The capacity of the plant is 45 stph, dropping to 35 stph when intense regrind is underway (maximum of 550 short tons per day of crushed and sized perlite). A Santa Fe Railroad spur extends about 2 miles from the center of Socorro to the Dicaperl mill. The ability to regrind coarser fractions to produce finer saleable product has recently been added to the processing circuit. This will reduce waste and increase profitability.

Dry -3/8 inch perlite is moved to a position above the storage tanks where it is screened again in one of two banks of screens. About eight different products are produced in 12 different storage tanks and these sizes can be blended to customer specifications. SOC 79 is the coarsest product and ranges from 6 to 20 mesh with about 50% +8 mesh. SOC 77 is also 6 to 20 mesh, but only about 5% is +8 mesh. SOC 75 is 12 to 50 mesh. Bin three material

does not have a SOC number, is 20 to 100 mesh, and is used internally in the company. SOC 67 is also 20 to 100 mesh, but with about 5% +30 mesh. The finer sizes are called coarse 0 ("ought"), double 0 and triple 0. Coarse 0 is called SOC 66 and is -20 to +100 mesh. This size is the preferred material for ceiling-tile production. SOC 65, or double 0, is coarse waste collected in the baghouse. About 75% is +325 mesh and all is -80 mesh. Triple 0 is the finer-size baghouse fines and is subdivided into SOC 54 and SOC 52. The finest (SOC 54) is 250 to 325 mesh.

About 98% of the crude perlite is moved from the Socorro facilities to customers by rail, primarily in 100 st bottom-dump railcars. Some is moved in PD railcars needed for pneumatic unloading of finer sizes. A Dresser 510 or 530 front-end loader moves railcars and product around the plant. About 2% of crude perlite is trucked to customers requiring perlite in 50 lb sacks or 1 m<sup>3</sup> super sacks. Dicaperl expansion plants are in Lafayette, Louisiana, and Jackson, Mississippi, and take about 10-15% of the total crude perlite production. Customers for the Socorro perlite are in Alabama, Arizona, California, Colorado, Florida, Georgia, Illinois, Indiana, Iowa, Kentucky, Michigan, New Mexico, Oklahoma, Pennsylvania, Tennessee, Texas, and Wisconsin. About 10% of the product



is exported to foreign countries, principally Canada, with a small amount to Mexico (Table 3). About 60% of the Socorro Dicaperl output goes for ceiling tile. Most of the remainder is used by the horticulture market and a minor amount goes into filter aids, wallboard, and pipe insulation.

### Harborlite Corporation (No Agua Peaks, NM and Antonito, CO)

The Harborlite mine and screening plant are at No Agua Peaks a few miles north of Tres Piedras and about 25 miles south of Antonito, Colorado, and northeast of the Dicaperl mine. The mine was opened in 1952-1953 at North Hill, northeast of the plant. Perlite occurs on top of each of the four No Agua Peaks and also on their flanks (see Dicaperl section above for geology). The hilltop perlite, particularly on the North Peak, called "North Hill" by mine employees, has excessive obsidian that caused mining to cease in 1981. Harborlite has about 1,500 acres of surface rights and an additional 500 acres of mining rights on the No Agua Peaks. Mining has disturbed 300-400 acres.

Since 1981, Johns Manville Corporation, the owner at the time, and subsequent owners (Celite and now Harborlite) concentrated on the flanks of South Hill on the both west (Area A) and east (Area B) sides, and the West Hill. The ore in this area is both granular and pumiceous, although some denser material similar to classical perlite is at the core of the hills (Photo 22). In general, a lateral progression from denser perlite, to granular to pumiceous exists from South Hill southward. Some fine-grained, gray-to-clear obsidian is present in the "classical" and granular perlite, but the pumiceous perlite contains virtually none.

The flanks are mined inward toward the core of the hill until the overlying rhyolitic rocks and overburden are too thick to strip. When the total Harborlite lease area and

the present rate of extraction are considered, at least a year supply of perlite is present. Perlite in West Hill differs from the other hills and is similar to adjacent Dicaperl on the east edge of the Dicaperl mine lies on the west flank of West Hill. Perlite is ripped 70-80% of the time (West Hill is all ripped; South Hill has some blasting), except the hardest classical perlite (Table 2). Blasting accounts for 20 to 30%, using ANFO and electric caps. The Komatsu 365 tractor with three rippers loosens the ore. Perlite is loaded with Caterpillar 992B front-end loaders with 3 yd<sup>3</sup> buckets onto three Euclid R50 mine trucks (50 st) for the 2-mile haul from the present pits to the screening plant.

At the screening plant, trucks deliver ore to an approximately 25,000 st stockpile. A Caterpillar 988 front-end loader moves ore to a grizzly (-2 foot) over a primary jaw crusher. Most of the +2-foot perlite is broken by load traffic over the grizzly. The primary crusher reduces perlite to -4 inch ore screened to -0.5 inch.

Sized crude perlite is shipped by company bottom-dump trucks 24 miles from the No Agua screening plant to the rail-loading facilities at Antonito, Colorado (Photos 23 and 24). Harborlite has six tractors that move to twin-bottom-dump trailers, five sets of 15 st bottom-dump trailers, and two pressure differential (PD) trailer pup trailers, and two pressure differential (PD) trailers. Typically, only 2-3 trucks are in use hauling ore between the mine/mill and the crushing plant. The ore is dumped by truck or Caterpillar 910 front-end loader into either a coarse or a fine circuit and moved by conveyor belt, or a vibrating screen, and into one of 11 silos that contain dried and sized perlite ore in seven standard sizes. Perlite size fractions can be blended to customer specifications. Multiple samples are taken from all railcars as they are loaded, allowing immediate adjustment and recording of what was sent to customers. Testing facilities are extensive and include a lab expansion furnace to aid in production and ore-grade control. Perlite is rescreened a last time during loading into bottom-dump or PD 100 st railcars (Photo 25) at the rate of about 30 bottom-dump and 1 PD railcars per week. Less than 5% of the ore is shipped by truck, mostly to local or small markets or those lacking rail service. Eight employees work at the Antonito facility in 8-hour shifts, five days a week plus scheduled overtime.

Harborlite supplies crude perlite to customers in California, Florida, Illinois, Minnesota, Mississippi, Pennsylvania, and Texas (Table 3). Some customers in California and Texas take fine perlite in PD cars. All perlite from the Harborlite No Agua Mine is sold to outside customers. About 50% goes into acoustical tile, 30% into fescue (rock board), 10% into filter aids, 5% into silica flux at foundries, 5% into horticulture, and a very small amount into microspheres. Perlite imported from Greece has little impact on markets at the present time, although some customers accept perlite from both Harborlite and Greece.



Photo 22. Perlite ore loaded in area "A" of the Harborlite mine on the South Hill of the No Agua Peaks in northern New Mexico. The ore in the background is mostly of the granular perlite.



Photo 23. Tractor truck with two "pups" dumping crushed and sized perlite from the Harborlite mine at No Agua, New Mexico, at Harborlite's storage and loading facilities near Antonito, Colorado.



Photo 25. Railroad loading facilities with 100 st railcars at the Harborlite facilities near Antonito, Colorado.



Photo 24. Sized crude perlite dropping through the bottom hatch of a hopper at the Harborlite facility in Antonito, Colorado.

### U.S. Gypsum

Volcanic rocks of East Grants Ridge, a few miles northeast of Grants in west-central New Mexico, consist of an older rhyolitic phase and a later mafic phase (Barker and others, 1989). The initial emplacement of the rhyolitic phase was a rhyolitic cinder cone that contains crystal-vitric ash of inter-layered pumice, powdery ash, and glass shards. A large dome of very pale-gray, thinly flow-banded rhyolite containing abundant small feldspar phenocrysts formed within the crater of the cinder cone. On the east side of the ridge the outer part of the rhyolitic body consists of concentric envelopes of perlite and obsidian. Potassium-argon dates on the obsidian and perlite indicate that the unit is  $3.3(\pm 0.3)$  m.y. old (Bassett and others, 1963).

The U.S. Gypsum (USG) operation at Grants, New Mexico, began in 1953 when USG bought about 1,600 acres (about 600 acres in perlite) of patented claims of the Pumice Corporation of America (PCA). PCA operated a pumice mine on the south side of East Grants Ridge. USG did not operate the pumice facility, but did open a perlite mine on a low hill at the east end of East Grants Ridge



called Hill No. 7. Perlite production peaked in 1957 and has since decreased to about 10,000 st mined in 1992. The present mine and mill are operated by four employees on four 8-hour shifts per week.

The open-pit mine covers 200 to 300 acres and has eight 25-foot benches so that the top of the original hill was about 200 feet above the base of the present mine. Early drilling indicated perlite present to depths of 1,300 ft below the former surface. At present the mine is operated by 1-2 people who work both as miners and truck drivers. A Caterpillar 988A front-end loader is used to mine the perlite ore and move it to a Mack tractor with a 26-foot end-dump trailer (Table 2). The ore, which is granular to pumiceous with no obsidian, is fractured in place and is easily broken by mining with the loader, so blasting is unnecessary (Photo 26).

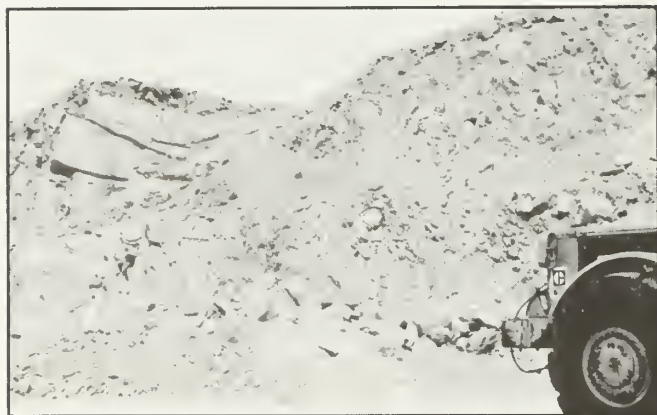


Photo 26. The highly fractured perlite ore at the U.S. Gypsum mine 9 miles northeast of Grants, New Mexico, is mined with a front-end loader (partly shown at the right).

The ore is trucked about 8 miles to the processing plant adjacent to the Santa Fe Railroad loading facility in Grants, where it is stored in a 0.5-acre stockpile before being moved with an Allis-Chalmers 745 front-end loader to the hopper that feeds a Nico-feeder Universal 3042 jaw crusher which reduces the ore to  $\pm 4$  inch. A conveyor belt moves the crushed ore into and to the top of the mill where a Tyrock screen separates the ore into two streams at about  $3/4$  inch. The coarser  $+3/4$  inch is reground in a Hydrocone 651 cone crusher and dumped into the circuit above the Tyrock screen. The  $-3/4$  inch ore goes into one of two storage tanks. Stored ore is later removed from below and fed into a 35-foot rotary dryer that is heated with natural gas. The perlite contains about 6% free moisture as it enters the dryer and has less than 0.5% when it leaves. Dried ore then goes to one of three roll crushers in series with four hummer screens producing the final size of -0.5 inch to +300 mesh (GA-1). Perlite in four sizes was produced, but current production is only in the GA-1 size. The -300 mesh material and baghouse fines

are trucked to the mine and used as road material, or dumped and covered.

Perlite is shipped from the Grants crushing plant primarily to USG plants in Indiana, New York, Ohio, Texas, where it is expanded and used in Thermofill plants (Table 3). The ore expands to 6-9 lbs/ft when expanded at 1,300-1,325°F. About 20% of the 1992 shipment of 3,850 st went to a customer in Missouri. About 98% production leaves Grants in 100 st bottom-dump rail cars at the rate of 2 to 3 per month (Photo 27). The price of crude perlite to local customers using trucks is about \$50/st FOB plant.



Photo 27. The railroad loading facilities behind the U.S. Gypsum crushing and sizing plant in Grants, New Mexico.

## TESTING COMMERCIAL PERLITE

Perlite grab samples were taken by the authors primarily in February 1993 during plant visits. Perlite Institute techniques modified by the NMBMMR were used to evaluate the samples (Tables 4 through 9). Refer to the Perlite Institute test manual (Perlite Institute, 1984) and Barker and Hingtgen (1985) for descriptions of the test apparatus, procedures, and calculations. The inexpensive Manual of Test Methods is available from the Perlite Institute at 88 New Dorp Plaza, Staten Island, NY 10314.

The samples taken by the authors were supplemented by previously collected samples or those delivered to the NMBMMR by perlite companies. Several standard tests were run to compare commercial perlites under near identical conditions. However, not all perlites are optimized for expansion at 1300°F, the temperature used, so the data show general trends rather than optimal performance. Two additional tests were made (Penfield water content and rock chemistry) to characterize commercial perlite by ore type and mine.



## TEST METHODS

Perlite deposits are evaluated for their suitability in their main end uses: horticulture, construction, filter aids, and fillers/extenders. Basic testing of expanded perlite measures suitability for horticulture. Additional tests of perlite are done for construction end uses. A special leaching regime is used to test filteraid perlite and chemical tests are added because of its use in the food industry. Perlite as a filler/extender is relatively new and testing procedures and specifications are non-standard or confidential. Crystalline-silica content of perlite is needed so that compliance related to health regulations can be determined.

Factors affecting perlite expansion are complexly interrelated. Expansion is a function of composition (especially water content), softening temperature, furnace temperature, and particle residence time in the flame. Perlite can be classified as "lively" or "dead" based on its water content and softening temperature (Murdock and Stein, 1950). "Dead" perlites have less combined water and higher softening temperatures than "lively" perlites of the same type. More heat must penetrate dead perlite particles to achieve good expansion. This can be accomplished by preheating the perlite feed, increasing the furnace temperature and/or the particle residence time in the furnace. Stein and Murdock (1955) concluded that the degree of expansion of a perlite

Table 4. Combined-water (Penfield method) analyses of grab samples taken from commercial U.S. Perlite mines.

STATE Company	Perlite Type (Sample No.)	Penfield H <sub>2</sub> O (wt%)	STATE Company	Perlite Type (Sample No.)	Penfield H <sub>2</sub> O (wt%)
<b>ARIZONA (Superior)</b>			<b>IDAHO (Malad)</b>		
Harborlite Corp.	Classical (1a)	1.70	National Perlite	Granular (1a)	2.62
	Classical (1a, dup)	1.90		Granular (1b)	2.53
	Classical (1b)	2.18		Granular (1c)	2.53
	Classical (1c)	2.13			
	Classical (2a)	2.23			
	Classical (2b)	2.07	<b>NEVADA (Caliente)</b>		
	Classical (2c)	1.72	Wilkin Trucking and Mining	Classical (1)	2.38
				Classical (2)	1.73
				Classical (3)	3.02
				Classical (4)	3.27
Nord Perlite	Granular (1a)	4.62	<b>NEW MEXICO</b>		
	Granular (1b)	3.78	Dicaperl		
	Granular (1c)	5.44	(No Agua)	Granular	2.40 <sup>1</sup>
	Classical (2a)	2.51			
	Classical (2b)	5.72	Dicaperl	Granular (1)	2.91
	Classical (2c)	4.06	(Socorro)	Granular (1, dup)	2.96
	Pumiceous (3a)	4.38		Granular (2)	3.18
	Pumiceous (3b)	4.60		Granular (3)	3.14
	Pumiceous (3c)	4.96		Granular (4)	3.10
<b>CALIFORNIA (Big Pine)</b>					
American Perlite	Granular (1a)	3.11	Harborlite Corp. (No Agua)	Classical (1a)	2.12
	Granular (1b)	3.04		Classical (1b)	2.43
	Granular (1c)	3.14		Classical (1c)	2.39
	Pumiceous (2a)	2.97		Pumiceous (2a)	2.92
	Pumiceous (2a, dup)	2.57		Pumiceous (2a, dup)	2.82
	Pumiceous (2b)	2.64		Pumiceous (2b)	2.87
	Pumiceous (2c)	2.97		Pumiceous (2c)	2.85
				Granular (3a)	1.91
<b>COLORADO (Florence)</b>				Granular (3a, dup1)	1.88
Persolite Perlite	Classical (1a)	4.50		Granular (3a, dup2)	2.07
	Classical (1b)	4.24		Granular (3b)	2.31
	Classical (1c)	4.48		Granular (3c)	2.34
	Breccia (2a)	4.89		Granular (4a)	2.59
	Breccia (2b)	5.09		Granular (4b)	3.33
	Breccia (2c)	5.21		Granular (4c)	3.32
			U.S. Gypsum (Grants)	Granular (1)	2.51
				Granular (2)	2.69
				Granular (3)	2.69
				Granular (4)	2.90

Average for Dicaperl granular perlite internal standard used during numerous NMBMMR perlite tests.

dup = duplicate sample

dup1, dup2 = separate duplicate samples

Analysis by the NMBMMR Chemistry Laboratory.

Table 5. Summary of combined-water analyses by perlite type given in Table 4 with means and standard deviations ( $\sigma$ ) of data.

STATE Company	Perlite Type	Penfield H <sub>2</sub> O Ave. wt.% (n)	Mine Ave. Penfield H <sub>2</sub> (n)	$\sigma$
ARIZONA (Superior)				
Harborlite Corp.	Classical	1.99 (7)	1.99 (7)	0.22
Nord Perlite	Granular	4.61 (3)	4.45 (9)	0.95
	Classical	4.10 (3)		
	Pumiceous	4.65 (3)		
CALIFORNIA (Big Pine)				
American Perlite	Granular	3.10 (3)	2.92 (7)	0.29
	Pumiceous	2.79 (4)		
COLORADO (Florence)				
Persolite Perlite	Classical	4.41 (3)	4.74 (6)	0.38
	Breccia	5.06 (3)		
IDAHO (Malad)				
National Perlite	Granular	2.56 (3)	2.56 (3)	0.05
NEVADA (Caliente)				
Wilkin Trucking and Mining	Classical	2.38 (4)	2.38 (4)	0.69
NEW MEXICO				
Dicaperl (No Agua)	Granular	2.40 (*)	2.40 (*)	—
Dicaperl (Socorro)	Granular	3.06 (5)	3.06 (5)	0.12
Harborlite Corp. (No Agua)	Classical	2.31 (3)	2.41 (15)	0.34
	Pumiceous	2.86 (4)		
	Granular	2.22 (8)		
U.S. Gypsum (Grants)	Granular	2.70 (4)	2.70 (4)	0.16

\*Numerous samples average 2.40 wt.%.  
Analyses by the NMBMMR Chemistry Laboratory.

particle is proportional to the temperature achieved in excess of its softening temperature.

Samples must be crushed and sized prior to expansion in an expansion furnace. Efficient expansion of perlite particles is highly dependent on their surface area to volume ratio. A narrow, unimodal size distribution is preferred for testing. The small size of the laboratory expansion furnace makes it sensitive to feed size and temperature. Expansion is best using the -50+100 mesh fraction at 1300°F, although the -30+50 mesh fraction can be used at higher temperatures.

No correlation has been demonstrated between bench-scale expansion tests using horizontal furnaces and similar tests in commercial plants. Scaling up from vertical-furnace bench testing to full-scale operation correlates better, but full-scale testing must be done prior to commitment of resources to investment, mining, or processing of perlite (Kadey, 1983).

### Determination of Total H<sub>2</sub>O By the Penfield Method

The total bound water the perlite samples was determined by a Penfield method modified from the Hillebrand and others (1953) procedure described in Kirschenbaum (1983, p. 36-37). The perlite sample is pulverized and predried at 105-110°C for 24 hours, as is the sodium-tungstate flux used in the procedure. All glassware is predried overnight at 160°C. The sample is mixed with flux in a Penfield tube placed in an oil bath on the capillary end and fused using oxygen/gas flame on the bulb end. The bulb is twisted off after fusing, gases are expelled with a dry run and the tube is corked and cooled. The decorked tube is weighed to four decimal places, dried for two days at 160°C, and reweighed. The Penfield water is the weight loss expressed as a percent weight (wt.%). Duplicate analyses of selected samples are run as a control.

Samples from all domestic commercial perlite mines were tested at the NMBMMR laboratories (Table 4). Some were tested in triplicate to determine the range of water values for a given sample. A summary of the combined-water analyses by perlite type for each mine with data means and standard deviations, shows some general trends (Table 5). Commercial perlite has combined water content from about 2 to more than 5 wt.%, although most perlite ore ranges from 2.5 to 3.0 wt.%. Water content is not tied to perlite types and all of the three major types (classical, granular, and pumiceous) have examples that are higher or lower than the average. Standard deviations of the data were less than 1 wt.% and as low as 0.05. The large operations, commonly mining granular perlite, appear to have the most uniform water content, but many exceptions occur because perlite formation is primarily by variable weathering of volcanic material.

The relation of combined-water content to density of expanded perlite is not obvious (Table 6). In general, the expanded perlite with the lowest density (1.9 lbs/ft<sup>3</sup>) was from granular crude perlite, but not always. Classical perlite also expands well, generally to less than 2 lbs/ft<sup>3</sup>, but it may be as high as 4.9 lbs/ft<sup>3</sup>. Only a few pumiceous perlites and perlite breccias were tested, limiting conclusions.

The combined-water content is not the only factor in producing a low-density expanded perlite. Based on the data in Table 4, at least 1.7 wt.% bound water (technically, obsidian is less than 2 wt.% bound water) must be present for expansion of commercial perlite, but more water does not always lower the density of the expanded product. Obsidian below 1.7 wt.% water is expanded commercially in special furnaces. The Persolite samples

Table 6. Test data for perlite grab samples (-50 to +100 mesh) from U. S. commercial perlite mines expanded at 1300° F without preheating.

STATE Company	Sample Type (Sample No.)	Average Penfield H <sub>2</sub> O (wt.%)	Furnace Yield (wt.%)	Expanded Density (lbs/ft <sup>3</sup> )	Average Brightness (%)	Non- Expansibles (wt.%)	Compacted Density (lbs/ft <sup>3</sup> )
<b>ARIZONA (Superior)</b>							
Harborlite Corp.	Classical (1)	1.98	99	4.44	53.1	12.2	ND
	Classical (2)	2.01	96	2.92	63.2	14.0	4.50
Nord Perlite	Granular (1)	4.61	88	1.74	47.6	11.0	ND
	Classical (2)	4.10	81	2.32	59.9	12.6	1.98
	Pumiceous (3)	4.65	75	2.50	69.3	18.4	ND
<b>CALIFORNIA (Big Pine)</b>							
American Perlite	Granular (1)	3.10	94	1.20	58.6	2.0	2.31
	Pumiceous (2)	2.79	94	1.84	69.0	1.2	2.52
<b>COLORADO (Florence)</b>							
Persolite Perlite	Classical (1)	4.41	80	4.91	68.3	8.2	6.95
	Breccia (2)	5.06	84	6.52	68.3	4.8	ND
<b>IDAHO (Malad)</b>							
National Perlite	Granular (1)	2.56	90	3.57	59.8	5.2	4.03
<b>NEVADA (Caliente)</b>							
Wilkin Trucking and Mining	Classical (1)	2.38	95	1.76	52.1	12.6	2.23
	Classical (2)	1.73	96	1.73	54.4	6.8	2.44
	Classical (3)	3.02	92	1.84	52.4	15.8	2.12
	Classical (4)	3.27	96	1.78	55.0	5.8	2.35
<b>NEW MEXICO</b>							
Dicaperl (No Agua)	(STD-1 <sup>1</sup> )	2.40 <sup>2</sup>	95	2.55	60.6	2.6	2.74
	(STD-1a)		95	3.48	67.0	2.8	3.81
	(STD-2)		96	2.73	60.7	0.8	ND
	(STD-2a)		94	2.78	60.8	0.2	ND
Dicaperl (Socorro)	Granular (1)	2.94	96	2.43	65.8	11.6	4.59
	Granular (2)	3.18	92	2.03	59.6	1.6	ND
	Granular (3)	3.14	90	1.94	68.2	5.4	3.02
	Granular (4)	3.10	87	2.30	66.2	5.2	ND
Harborlite Corp. (No Agua)	Classical (1)	2.31	96	1.51	60.1	1.2	1.87
	Pumiceous (2)	2.86	93	1.97	62.2	16.2	2.36
	Granular (3)	2.10	95	2.97	62.1	16.0	3.58
	Granular (4)	3.08	94	1.66	63.7	3.2	2.31
U.S. Gypsum (Grants)	Granular (1)	2.51	95	2.17	55.4	12.8	2.85
	Granular (2)	2.69	85	3.27	66.5	0.4	ND
	Granular (3)	2.69	96	6.05	60.9	2.2	ND
	Granular (4)	2.90	95	12.65	50.4	4.8	ND

ND=not determined, sample too small.

<sup>1</sup>Split of NMBMMR perlite standard; a large homogenized sample from Dicaperl's No Agua Mine.

<sup>2</sup>Average water content from many splits of past homogenized standard sample.



Table 7. Sieve analyses of perlite (-50 to +100 mesh) at 1300°F expanded with no preheating.

STATE Company	Sample Type (Sample No.)	Weight Percent Retained on Sieve (Mesh)							PAN	Total
		20	30	50	70	100	140			
ARIZONA (Superior) Harborlite Corp.	Classical (1)	0.6	5.4	77.0	15.2	0.9	0.4	0.5	100.0	
	Classical (2)	4.3	23.3	55.8	9.9	3.6	2.7	0.4	100.0	
Nord Perlite	Granular (1)	17.0	13.1	37.0	14.8	6.8	6.2	5.1	100.0	
	Classical (2)	11.0	14.0	33.4	13.9	10.0	1.3	16.4	100.0	
	Pumiceous (3)	0.9	2.8	21.2	16.0	13.1	22.1	23.9	100.0	
CALIFORNIA (Big Pine) American Perlite	Granular (1)	3.5	18.9	47.4	15.2	5.7	6.8	2.5	100.0	
	Pumiceous (2)	13.3	32.6	39.1	6.9	2.6	2.7	2.8	100.0	
COLORADO (Florence) Persolite Perlite	Classical (1)	2.0	1.8	21.7	14.6	13.9	14.6	31.4	100.0	
	Breccia (2)	1.4	2.0	33.3	18.0	12.3	11.3	21.6	98.5	
IDAHO (Malad) National Perlite	Granular (1)	2.9	23.8	54.3	12.7	3.9	1.1	1.3	100.0	
NEVADA (Caliente) Wilkin Trucking and Mining	Classical (1)	14.0	26.5	39.4	12.3	5.6	1.2	1.0	100.0	
	Classical (2)	12.8	27.7	32.9	18.0	4.8	2.2	1.6	100.0	
	Classical (3)	14.7	30.3	38.1	9.4	4.4	1.7	1.4	100.0	
	Classical (4)	18.9	33.2	35.3	7.2	2.8	1.3	1.3	100.0	
NEW MEXICO Dicaperl (No Agua)	(STD-1')	7.5	26.2	51.9	7.3	2.7	2.3	2.1	100.0	
	(STD-1a)	3.7	32.8	53.9	7.1	1.6	0.9	0.0	100.0	
	(STD-2)	2.6	34.4	49.4	7.8	2.9	1.4	1.5	100.0	
	(STD-2b)	2.0	34.1	46.9	5.9	8.1	1.4	1.6	100.0	
Dicaperl (Socorro)	1 Granular	1.0	19.4	49.7	15.1	7.2	4.3	3.3	100.0	
	2 Granular	ND	ND	ND	ND	ND	ND	ND	ND	
	3 Granular	3.0	23.4	44.5	13.7	6.1	4.7	4.6	100.0	
	4 Granular	5.6	26.2	39.0	13.0	6.0	5.0	4.7	99.5	
Harborlite Corp. (No Agua)	Classical (1)	15.5	29.6	39.2	12.1	2.1	1.0	0.5	100.0	
	Pumiceous (2)	4.0	21.2	46.8	14.9	5.6	2.8	1.5	96.8	
	Granular (3)	2.0	15.0	56.3	12.9	3.0	10.0	0.8	100.0	
	Granular (4)	8.7	33.3	42.9	7.8	3.6	2.2	1.5	100.0	
U.S. Gypsum (Grants)	Granular (1)	1.6	14.9	59.1	14.7	5.7	2.6	1.4	100.0	
	Granular (2)	1.0	31.8	55.7	6.0	1.5	1.1	2.9	100.0	
	Granular (3)	0.1	6.7	79.3	11.6	1.4	0.3	0.6	100.0	
	Granular (4)	0.1	1.6	68.4	24.2	3.1	0.9	1.7	100.0	

<sup>1</sup>Split of NMBMMR perlite standard; a large homogenized sample from Dicaperl's No Agua mine.

ND=Not determined; no sample or sample too small.

with the highest water content produced higher densities of 5.0 to 6.5 lbs/ft<sup>3</sup> for the expanded product (Table 6). Oerlite from the Nord operation, with water content almost as high at 4.0 to 4.6 wt.%, produced expanded perlite with densities below 2.5 lbs/ft<sup>3</sup>. Samples from the U.S. Gypsum mine, with nearly the same water content (2.5 to 2.9 wt.%), produced an expanded product with widely divergent densities (2.0 to 12.6 lbs/ft<sup>3</sup>).

Average brightness of the expanded products of samples tested ranged from 47.6 to 69.3%. The few pumiceous perlites produced the highest brightness. On average, expanded classical perlite produced slightly lower brightness than granular perlites, with many exceptions.

Nonexpansible materials ranged from over 18% to less than 1 wt.% (Table 6). The nonexpansible are commonly obsidian or dead perlite, as well as quartz minerals, feldspar, biotite, magnetite, other accessory minerals, and products of devitrification (Kadey, 1983). In general, granular perlites had the lowest nonexpansibles; classical and pumiceous perlite had the highest. Compacted density did not appear to be related to either perlite type or nonexpansibles present.

Sieve analyses of the -50+100 mesh product show a wide variation in the size of the expanded product with a range of 19 to 0.1 wt.% +20 mesh product and 24 to 0.0 wt.% -140 mesh material (Table 7). In general,

Table 8. Crystalline-silica content of grab samples of crude commercial perlite from the western United States.

STATE Company	Perlite Type (Sample No.)	Value (wt.%)	STATE Company	Perlite Type (Sample No.)	Value (wt.%)
ARIZONA (Superior)	Harborlite		NEVADA (Caliente)	Wilkin Trucking	
	Classical (1a)	0.10		Classical (1)	ND
	Classical (1b)	ND		Classical (2)	ND
	Classical (1c)	0.07		Classical (3)	ND
	Classical (2a)	ND <sup>f</sup>		Classical (4)	ND
	Classical (2b)	0.06 <sup>f</sup>	NEW MEXICO		
				Dicaperl	
	Nord Perlite			Granular (1 <sup>2</sup> )	ND
	Granular (1a)	ND		Granular (2 <sup>2</sup> )	0.09
	Granular (1b)	ND		Granular (3 <sup>2</sup> )	0.17
	Granular (2a)	ND <sup>c</sup>			
	Classical (2b)	ND <sup>c</sup>		Harborlite	
	Classical (2c)	0.08 <sup>c</sup>		(No Agua)	
	Pumiceous (3a)	ND		Classical (1a)	ND <sup>f</sup>
	Pumiceous (3b)	ND		Classical (1b)	ND <sup>f</sup>
	Pumiceous (3c)	ND		Classical (1c)	ND <sup>f</sup>
CALIFORNIA (Big Pine)	American Perlite			Pumiceous (2a)	
	Granular (1b)	ND		ND	
	Granular (1c)	ND		Pumiceous (2b)	ND
	Pumiceous (2a)	ND		Pumiceous (2c)	ND
	Pumiceous (2b)	ND			
	Pumiceous (2c)	ND		Granular (3a)	ND
COLORADO (Rosita)	Persolite Perlite			Granular (3b)	ND
	Classical (1a)	DU <sup>f</sup>		Granular (3c)	ND
	Classical (1b)	DU <sup>f</sup>			
	Classical (1c)	DU <sup>f</sup>		Granular (4a)	0.10
	Breccia (2a)	0.10		Granular (4b)	0.15
	Breccia (2b)	ND		Granular (4c)	0.19
	Breccia (2c)	0.12	Dicaperl (Socorro)	Granular (1)	DU <sup>f</sup>
UTAH (Malad)	National Perlite			Granular (2)	DU <sup>f</sup>
	Granular (1a)	DU <sup>f,m,ca</sup>		Granular (3)	DU <sup>f</sup>
	Granular (1b)	DU <sup>f,m,ca</sup>		Granular (4)	DU <sup>f</sup>
	Granular (1c)	DU <sup>f,m,ca</sup>	U.S. Gypsum (Grants)	Granular (1)	DU <sup>f</sup>
	Granular (2 <sup>1</sup> )	0.15		Granular (2)	DU <sup>f</sup>
				Granular (3)	DU <sup>f</sup>
				Granular (4)	DU <sup>f</sup>

determined in the NMBMMR X-ray Facility by x-ray diffraction.  
Note that silica values change during expansion and with blending.

D = Below the detection limit of 0.05 wt.%.  
U = Data unreliable because of interference.

<sup>f</sup>Feldspar interference present; data, if reported, are therefore maxima.

<sup>c</sup>Clay mineral interference present.

<sup>m</sup>Mica interference present.

<sup>ca</sup>Calcite interference present.

Average of samples supplied by National Perlite and analyzed previously; (n=6,  $\sigma$ =0.09).

Archive data from previously collected samples.

Pumiceous perlites tend to produce less coarse expanded product. Classical and granular perlites have expanded products that average 60 to 80% -30+100 mesh.

### Crystalline-Silica Content by X-Ray Diffraction

Quartz can cause pulmonary fibrosis (silicosis) if exposure is prolonged, and it is a possible carcinogen according to the International Association for Research on Cancer (IARC). Mixtures or materials containing more than 0.1 wt.% free silica may need to be labeled. Three

polymorphs of crystalline silica are common, but quartz is by far the most abundant form in perlite. Research initially concentrated on trace analysis of quartz in perlite by x-ray diffraction.

Grab samples of crude perlite taken by the authors from each of the 10 operations were examined by x-ray diffraction (Table 8). The crystalline-silica detection limit at the NMBMMR X-ray Facility is 0.05 wt.%. At these low concentrations, reflections from other crystalline substances on x-ray traces, notably feldspar, clay minerals, mica, and/or calcite, may obscure crystalline-silica reflections. The values from the majority of samples tested ranged from below the detection limit (ND) to nearly 0.2 wt.%. Interference by other crystalline substances obscured silica reflections of 14 samples. Therefore, the values reported in Table 8 should be considered *maxima* owing to additive interference by accessory minerals. The process used to produce expanded perlite affects crystal-

Table 9. Major and minor oxide chemistry by X-ray fluorescence on grab samples of selected commercial perlites in the Western United States in weight percent.

STATE/Sample	SiO <sub>2</sub>	TiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	Fe <sub>2</sub> O <sub>3</sub>	MnO	MgO	CaO	Na <sub>2</sub> O	K <sub>2</sub> O	P <sub>2</sub> O <sub>5</sub>	LOI	Total
<b>ARIZONA</b> (Superior)												
Harborlite 2b	75.184	0.091	13.042	0.654	0.082	0.157	0.821	4.201	4.728	0.063	2.660	101.683
Harborlite 2c	75.111	0.079	12.983	0.592	0.059	0.317	0.814	3.962	4.569	0.052	2.650	101.186
Nord 1a												
Nord 1c	71.936	0.122	12.954	0.709	0.086	0.921	0.949	1.902	4.987	0.052	7.370	101.986
Nord 3a	71.002	0.117	12.601	0.676	0.078	0.582	0.858	1.992	5.051	0.043	7.120	100.121
Nord 3b	72.003	0.088	12.131	0.639	0.058	0.236	0.549	2.710	5.177	0.051	5.420	99.063
Nord 3c	73.140	0.130	12.292	0.729	0.076	0.226	0.571	2.458	5.350	0.045	5.300	100.317
Nord 3c	72.646	0.111	12.192	0.683	0.077	0.212	0.597	2.594	5.240	0.046	5.470	99.866
<b>CALIFORNIA</b> (Big Pine)												
American 1b	74.585	0.077	13.032	0.731	0.095	0.084	0.600	4.004	4.854	0.059	3.490	101.611
American 2a	74.251	0.090	13.052	0.719	0.104	0.439	0.564	4.252	4.627	0.061	3.450	101.611
American 2b	74.592	0.065	12.859	0.646	0.085	0.105	0.530	4.231	4.616	0.050	3.350	101.129
<b>COLORADO</b> (Florence)												
Persolite 1c	74.000	0.083	12.284	0.719	0.162	0.106	0.385	3.034	5.090	0.052	4.960	100.875
<b>IDAHO</b> (Malad)												
National 1a	76.175	0.087	12.134	1.047	0.035	ND	1.020	3.188	4.484	0.048	3.070	101.241
National 1c	75.011	0.089	12.082	1.063	0.038	0.472	1.258	3.279	4.393	0.074	3.520	101.279
<b>NEVADA</b> (Caliente)												
Wilkin 2	75.038	0.082	12.825	0.821	0.061	ND	0.789	3.187	5.111	0.060	3.300	101.273
Wilkin 3	72.919	0.105	12.514	0.844	0.055	0.162	0.786	3.253	4.901	0.070	3.400	99.008
Wilkin 4	72.697	0.112	12.389	0.792	0.061	0.052	0.787	2.918	5.007	0.058	3.700	98.571
<b>NEW MEXICO</b>												
Dicaperl Socorro 4	74.821	0.045	12.348	0.459	0.084	0.047	0.477	3.429	5.097	0.055	3.310	100.172
Harborlite 1a												
Harborlite 1b	75.339	0.070	13.011	0.627	0.067	0.320	0.821	4.086	4.680	0.062	2.890	101.973
Harborlite 1c	74.421	0.076	12.707	0.647	0.068	ND	0.779	3.921	4.613	0.046	2.920	100.139
Harborlite 4a	74.935	0.074	13.035	0.619	0.055	0.127	0.762	4.034	4.721	0.048	3.320	101.729
Harborlite 4b	72.993	0.047	12.329	0.518	0.130	0.019	0.458	4.393	4.125	0.048	3.740	98.800
Harborlite 4c	75.064	0.062	12.730	0.566	0.125	0.302	0.535	4.414	4.266	0.054	3.780	101.898
Harborlite 4c	74.627	0.053	12.535	0.541	0.131	ND	0.493	4.242	4.212	0.046	3.800	100.664
U.S. Gypsum 1												
U.S. Gypsum 3	74.479	0.019	12.940	0.750	0.104	0.125	0.530	4.439	4.343	0.048	3.370	101.147
U.S. Gypsum 4	73.525	0.031	12.820	0.754	0.106	0.140	0.528	4.323	4.293	0.048	3.340	99.908
U.S. Gypsum 4	75.575	0.037	13.084	0.744	0.104	ND	0.571	4.525	4.412	0.040	1.000	100.083

Determined in the NIMBMMR X-ray Facility on a wavelength dispersive spectrometer equipped with an Rh-target X-ray tube.  
Machine settings: generator settings: kV = 35; mA = 75; dead time = 1.90 microseconds.



the silica differently, so each product must be evaluated to determine silica content before shipment to customers. Expanding low-quartz crude with high-quartz perlite before expansion lowers quartz content of most expanded products. Recent environmental concerns for crystalline-silica content (most commonly quartz, cristobalite, and tridymite) of products prompted producers to determine the amount and mineralogy of silica minerals present in their perlite products.

Traditional x-ray diffraction (XRD) analysis of quartz in industrial dusts uses well established procedures (Klug and Alexander, 1974) that are sensitive to quartz at the 1 wt.% level. Trace analysis of <0.1 wt.% quartz in the samples was by x-ray diffraction (Hamilton and Peletis, 1989) using rotating pressed-powder briquettes (Renault, 1984), peak deconvolution (Wiedemann and others, 1987a,b), and standardization using artificial mixtures of quartz and common silica glass (Barker and McKee, 1989; McKee and others, 1990a,b; Renault and others, 1991, 1992).

#### **Major- and Trace-Element Chemistry by X-Ray Fluorescence**

The chemistry of commercial perlites is that of rhyolite (Table 9), and variations between the samples analyzed were subtle. Weathering at or near the surface may alter the chemical makeup of some perlites, such as clay minerals increasing the  $K_2O$  in the Nord (Superior, Arizona) samples or calcite boosting the  $CaO$  in the Malad, Idaho, samples from National Perlite (Table 9). Such minerals are commonly present as infilling of cracks and fissures developed during or after perlite emplacement.

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# Geology of Western U.S. Talc Deposits

by  
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## ABSTRACT

California was a major talc-producing State until the late 1980s when production from the deposits in the Death Valley area ceased because of a number of factors which included pressure to discontinue mining in and around Death Valley National Monument, and health concerns affecting markets for tremolitic talc. The states of Montana and Texas now account for slightly more than half of U.S. talc production.

Deposits in an area encompassing southern Death Valley and extending east into the Kingston Range were formed by contact metamorphism of carbonate beds in the Precambrian Crystal Spring Formation next to Precambrian diabase sills. These deposits contain ore ranging from high-purity, fine-grained talc to platy, tremolitic talc with high brightness. Deposits of tremolitic talc and talc schist in the Silver Lake District in San Bernardino County resulted from metamorphism of Precambrian carbonate rocks intruded by granitic plutons. Northeast in Esmeralda County, Nevada hydrothermal alteration related to Late Jurassic plutons caused talc replacement of Precambrian to Early Cambrian dolomite. A hydrothermal origin is also indicated for talc deposits in the Inyo Range just north of the Death Valley District where bodies of unusually pure talc occur in Paleozoic limestone near Jurassic granitic plutons. Talc is now mined from a deposit in the foothills of the Sierra Nevada Range southeast of Sacramento where quartz-mica schist of the Permian Calaveras Formation has been hydrothermally altered to talc.

Replacement of magnesite of the Precambrian Allamoore Formation produced talc deposits mined in the Allamoore District of west Texas. This dark-gray talc of low iron content with carbonaceous material and dolomite is ideally suited for use in ceramics where it makes a white product when fired. Small bodies of platy light-pink to white talc suitable for use as an extender in paint are also mined in this district. In the Llano District of central Texas talc is replaced impure carbonate rocks and serpentinite.

All Montana talc production is from deposits in the southwestern part of the State that formed by Precambrian hydrothermal alteration of dolomitic marble. This alteration produced material with high purity that ranges from very fine-grained, massive talc to coarser grained, platy talc. Markets include pitch control in paper, paint, cosmetics, ceramics, rubber and plastics.

In southwestern and northeastern Oregon, talc has replaced serpentinite in the vicinity of Mesozoic plutons. Soapstone for carving is mined from a southwestern Oregon deposit. Deposits of similar origin occur in central and northwestern Washington.

## INTRODUCTION

Major talc deposits in the Western U.S. are in the states of California, Montana, Texas, Nevada and Oregon (Figure 1). The diversity in precursor rock types and in talc-forming processes is responsible for differences in texture, mineralogy and chemical composition of the talc. These differences influence suitability of talcs for specific markets. Ores from Western U.S. deposits range from very fine-grained, platy talcs of high purity (Montana, for example) to dark-gray ceramic talcs from west Texas (Table 1).

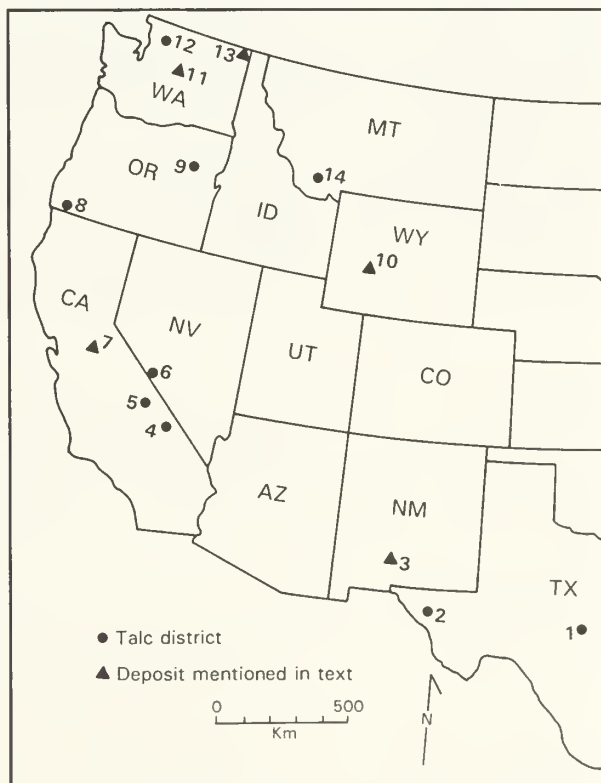


Figure 1. Talc districts and some deposits of the western U.S.  
1 - Llano, Texas; 2 - Allamoore, Texas; 3 - Red Rock Mine, New Mexico; 4 - Death Valley, Kingston, Silver Lake area, California; 5 - Inyo County, California; 6 - Esmeralda County, Nevada; 7 - Red Hill Mine, California; 8 - Southwestern Oregon; 9 - Northeastern Oregon; 10 - Sublette County, Wyoming; 11 - Entiat, Washington; 12 - Skagit County, Washington; 13 - Metalline Falls, Washington; 14 - Southwestern Montana.



Table 1. Summary information on western U.S. talc districts

District and References	Host Rock	Dominant Talc-Forming Process	Minerals in Addition to Talc	Texture
Texas Allamore (4,5)	Precambrian magnesite	Hydrothermal	carbonaceous material, dolomite, quartz	fine grained
Llano (1)	Precambrian schist, serpentinite and gneiss	Metamorphism	tremolite, chlorite, magnesite	coarse grained
California Silver Lake (13)	Precambrian carbonates	Metamorphism	tremolite, chlorite, serpentine, forsterite, minor calcite	both equant and platy
Death Valley - Kingston (14)	Precambrian carbonates	Metamorphism	tremolite, chlorite, carbonate minerals	from very fine grained to platy
Inyo County (10)	Paleozoic limestone	Hydrothermal	high purity -- rare pyrite	massive, fine grained
Sierra Nevada foothills (12)	Permian schist	Hydrothermal		
Nevada Esmeralda Co. (11)	Precambrian and Cambrian carbonates	Hydrothermal	chlorite, trace quartz calcite, dolomite, rare sericite	very fine grained massive talc
Oregon Southwest (6)	Paleozoic and Mesozoic	Metamorphism Hydrothermal	chlorite, ankerite, pyrite	foliated
Northeast (6)	Paleozoic and Mesozoic	Metamorphism Hydrothermal	dolomite and magnesite or amphiboles	foliated
Washington Central (9) Skagit Co. (9) Metalline Falls (9)	Pre-tertiary ultramafics Pre-tertiary ultramafics Proterozoic sed. rocks	Metamorphism Metamorphism Hydrothermal	tremolite, ankerite, pyrite chlorite, mica, quartz tremolite	foliated foliated fine grained massive
Montana Southwestern (2,3)	Precambrian dolomitic marble	Hydrothermal	chlorite, dolomite	fine grained, massive
New Mexico Red Rock (7)	Precambrian carbonate or phyllite			
Wyoming, Sublette Co.	Precambrian	metamorphic		soapstone

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- |                            |                                 |                  |
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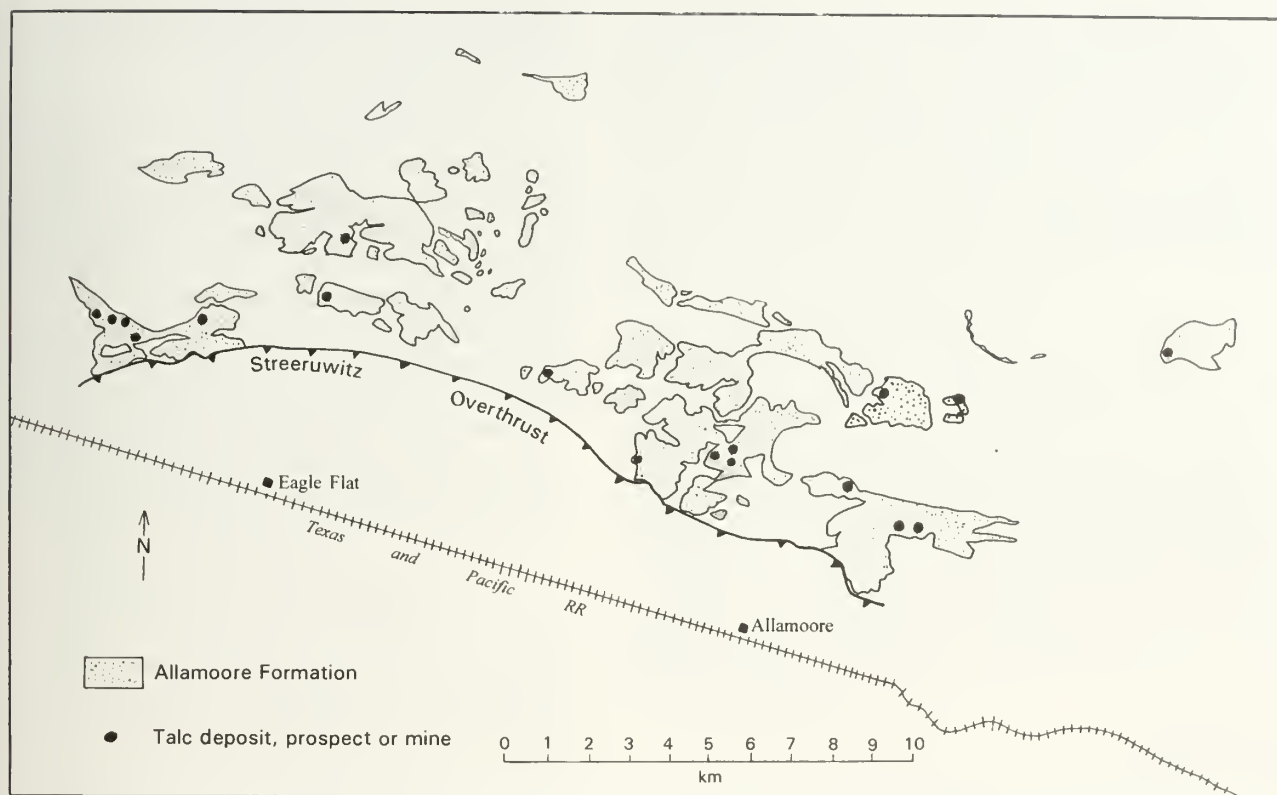


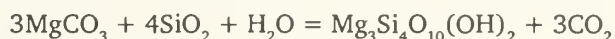
Figure 2. Talc deposits in the Allamoore District, Texas. Geology simplified from King, 1965, Plate 1. Deposits from Mineral producers data base, 1992, (unpublished data base of the Texas Bureau of Economic Geology) and Flawn, 1958.

## TEXAS

Texas has become a major talc producing State with production from the Allamoore District in Hudspeth and Person counties of west Texas (Figure 2). This district is a relatively new source of talc with production beginning in 1952 (Flawn, 1958, p. 104). Five companies produced 227,138 metric tons (mt) from these deposits in 1990, making Texas second to Montana in domestic talc production (White and Garner, 1992). Most talc from the Allamoore district is dark gray to black because of interbedded black carbonaceous material. In addition to carbonaceous material this dark talc contains dolomite and quartz. Mineralogy and texture of this talc make it well suited for the ceramic industry (Gensberg, 1978). Prior to firing, much of this talc is calcined to drive off  $\text{CO}_2$ , reducing the firing shrinkage. During this process carbonaceous material is also lost yielding a white product consisting of enstatite. Calcined talc is blended with talc from this district to produce a feed with low firing shrinkage suitable for the manufacture of wall tile and other ceramic products. The low iron content of this talc enables manufacturers to produce a white tile.

Talc deposits in this district are in the Precambrian Allamoore Formation which consists of interbedded siltstone, limestone, dolostone, probable lava flows and granite. The phyllitic unit, 30 m thick, is described as

"sericitic and graphitic, with some blue-black hornstone and gray calcareous layers" (King and Flawn, 1953, p. 80). Talc formed by selective replacement of magnesite beds in the phyllite originates by the following reaction (Bourbon, 1982, p. 82):



Because there was sufficient  $\text{SiO}_2$  in these beds for this talc-forming reaction, only the addition of  $\text{H}_2\text{O}$  was necessary. Talcose zones in the phyllite are as much as 160 m wide and 2 km long. Alternating light and dark gray laminae in the talc are attributed to cryptalgal structure (Bourbon, 1982, p. 80). Dolomite is more abundant in the lighter laminae. Most talc deposits in this district are within two kilometers of the trace of a Precambrian thrust fault (Figure 2). Intense deformation of the talcose phyllite is presumably related to movement on this fault.

A small amount of coarser grained, white or light-pink talc used as an extender in paint is also mined. Some of this lighter talc may have formed by hydrothermal alteration of the dark phyllitic talc by heat generated along faults (Edwards, 1984, p. 178).

Soapstone occurrences are widespread in Precambrian metamorphic rocks exposed in the Llano Uplift of central Texas; those with the greatest economic potential are situated in northeastern Gillespie County (Barnes and

Mathis, 1942). Lensoid masses of soapstone with surface exposures ranging from 0.6 to 1.8 m in width and 24 to 60 m in length occur in schist, serpentinite and gneiss. Tremolite, chlorite, and magnesite typically occur in addition to talc. It is thought that the soapstone formed in two successive steps; metamorphism of carbonate units in the Packsaddle Schist produced tremolitic schist which was later replaced by talc.

## CALIFORNIA

California talc deposits formed under diverse geologic conditions and have varied characters. The Silver Lake deposits were formed by contact metamorphism of carbonate units in a terrain extensively invaded by Mesozoic granitic plutons, whereas the deposits in the Death Valley-Kingston Range area were formed by contact metamorphism next to Precambrian diabase sills. In the Inyo Range to the north, hydrothermal activity related to Jurassic plutons replaced Paleozoic carbonate beds by steatite-grade talc. In the foothills of the Sierra Nevada Range, talc formed by the hydrothermal replacement of Permian beds.

### Silver Lake

The Silver Lake talc deposits, situated north of Baker in San Bernardino County (Figure 3), formed when Precambrian (?) metasedimentary rocks were intruded by dikes and irregular bodies of basic to intermediate composition, and by younger granitic bodies (Wright, 1954). Mined deposits typically consisted of two parallel, steeply-dipping talc bodies, each of which ranged in width from 3 to 4.5 m. These bodies are confined to a hornfels unit in the metasedimentary rocks. Within the hornfels unit, rock ranges in composition from almost entirely all tremolite to essentially pure talc. Both equant and platy talc occur in the tremolitic rock. In addition to talc and tremolite, some talc ore contains chlorite (?), serpentine, forsterite and minor calcite. Some of the talcose rock is schistose with individual talc flakes as large as 1 cm across. Wright (1954) recognized five stages of metamorphism beginning with the formation of anhydrous minerals and the later formation of tremolite which was altered to talc schist along shear zones.

### Death Valley Region

Deposits in the Death Valley region have been a major source of talc with maximum production occurring in the 1970s. Production from the mines in this area ceased in the late 1980s and was caused in part by concern about mining in and around Death Valley National Monument. In addition, the presence of tremolite in talc ore—even in very low concentrations—curtailed some important markets. The only producing mine in the general vicinity of Death Valley National Monument is the Canyon Mine

(Crystal Spring Mine) on the north flank of the Kingston Range about 40 km east of Death Valley National Monument (Figure 3).

Mines in the southeastern part of the Panamint Range have been very important sources of talc. The large underground Grantham Mine, which includes the Talc and #5 mines, has produced more talc than any other California mine (Evans, Taylor and Rapp, 1976, p. 10). Talc from Death Valley deposits, although all of the same origin, varies substantially in mineralogy and texture from very fine-grained high-purity talc to coarser-grained tremolitic, platy talc. Substantial variations in purity and texture of talc ore occur even within one deposit. Platy tremolitic talc with high brightness is well suited for use as an extender in paint and was extensively marketed for this application. Also, tremolitic talc with its low iron content was used in high-quality wall tile.

The geology of talc deposits in the Death Valley region was well described by Wright (1952, 1954, 1968) and is summarized by Evans, Taylor and Rapp (1976) in their discussion of the mineral resources of the Death Valley National Monument. The following summary is from these references. All talc deposits in the Death Valley region occur in the Crystal Spring Formation, the lowest formation of the Pahrump Group of Precambrian age. This group overlies Precambrian metamorphic rocks and is overlain by the Cambrian Noon Dolomite. The Crystal Spring Formation ranges up to approximately 1280 m in thickness and consists of quartzite,

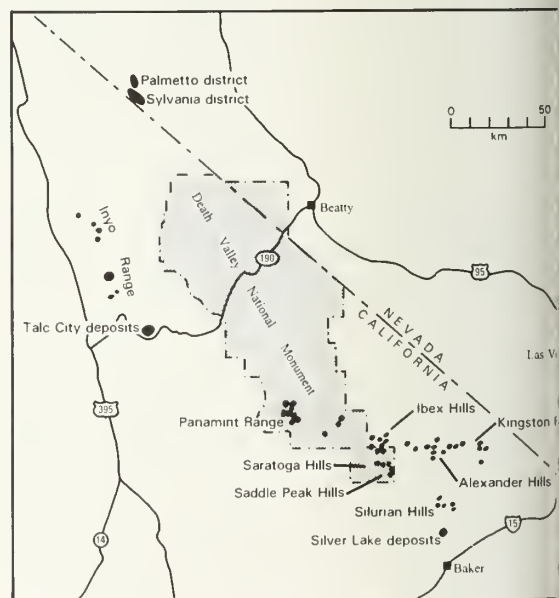


Figure 3. Talc deposits of southern California and Esmeralda County, Nevada compiled from the following sources. Palmetto and Sylvania districts, Nevada, Papke, 1975; Inyo Range and Talc City, California, Page, 1951; Panamint Range and the Kingston Range, California, Wright, 1954; and Silver Lake deposits, California, Wright, 1954. Larger areas indicate several closely-spaced prospects or mines.



shale, carbonates and chert. The carbonate member in the middle of this formation is the host for talc deposits; it contains both limestone and dolomite beds with some chert layers and quartzite beds.

Talc bodies, mainly within sills, are restricted to zones of silication next to Precambrian diabase intrusives. An extensive diabase sill is recognized to occur over much of this district and is at the base of the carbonate member. This sill is at least 120 km by 24 km in lateral dimension with thicknesses ranging from 15 m to 460 m (Wright, 1968, p. 13). The intrusion of diabase magma into carbonate beds, some siliceous, caused widespread silication and talc formation. Wright (1968, p. 15) suggested that these base sills were emplaced at shallow depth when beds of the Crystal Spring Formation were still poorly consolidated and water saturated. Extensive alteration of the base sill is judged to be deuteric.

Some of the talc ore bodies in the silicated zone are more than 1 km long and are typically 3 to 6 m wide (Wright, 1968, p. 5). The material varies from rock consisting mainly of talc to tremolitic talcose rock (Figure 3). Calcite and dolomite are present in most of the ore.

#### Inyo County

Nine talc deposits occur over a north-south distance of 43 km in the Inyo Range. Farther to the southeast, between the small communities of Keeler and Darwin, there are nine more talc deposits including the Talc City Mine (Figure 3). The Talc City Mine was a very important source of steatite which was machined and then fired to make high-frequency insulators (Page, 1951). Talc deposits in the Inyo Range differ from those in the Death Valley-Kingston region or in the Silver Lake area. The host rock for the Inyo Range talc deposits is Paleozoic limestone and quartzite, which has been altered to dolomite by hydrothermal fluids, and is presumably related to nearby Jurassic granitic plutons (Page, 1951). At the Talc City Mine granite is exposed within 915 m of the talc ore body. Limestone has been replaced by massive dolomite interpreted to be hydrothermal in origin. Talc bodies are restricted to this massive dolomite and are thought to have resulted from the introduction of  $\text{SiO}_2$ . Prior to the introduction of hydrothermal activity, the host rocks were folded, faulted, and created permeable zones which aided movement of the hydrothermal fluids which followed. A material—referred to as “silica rock”—is associated with the talc ore bodies and is typically surrounded by dolomite. The silica rock, which occurs in bodies of irregular shape, may be either quartzite or hydrothermal quartz. Its association with talc bodies and its occurrence in hydrothermal dolomite suggest a hydrothermal origin, however, photomicrographs show a granular texture suggestive of quartzite (Page, 1951; Figure 7). The introduction of  $\text{CO}_2$  after formation of the silica rock is indicated at four

deposits in the vicinity of the Talc City Mine where siliceous rock has been replaced by talc. With the exception of two deposits in the northern part of the district, all other deposits formed by replacement of dolomite.

Much talc from the Inyo Range is of steatite grade, a variety of massive talc of exceptional purity. Steatite from the Inyo Range is fine grained, massive, typically pale green in hand specimen and composed of anhedral talc grains 0.005 to 0.5 mm in maximum dimension (Page, 1951, p. 12). Pyrite, or its alteration product limonite, and calcite are found in some talc. Talc ore bodies are generally very irregular and range in size from a few hundred to a few thousand tons.

The White Eagle Mine in the central part of the Inyo Range is an unusual deposit formed in part by talcification of granite. Paleozoic quartzite and dolomitic limestone, intruded by a granitic pluton, have also been replaced by talc (Wright, 1948). This may be the only mine in North America where part of a talc ore body formed by the replacement of granite.

#### Sierra Nevada Foothills

Talc is now mined at the Red Hill Talc Quarry situated in the foothills of the Sierra Nevada Range southeast of Sacramento (Figure 1). The host is the Calaveras Formation of Permian age which consists of argillaceous rocks and siltstone with thin-bedded chert

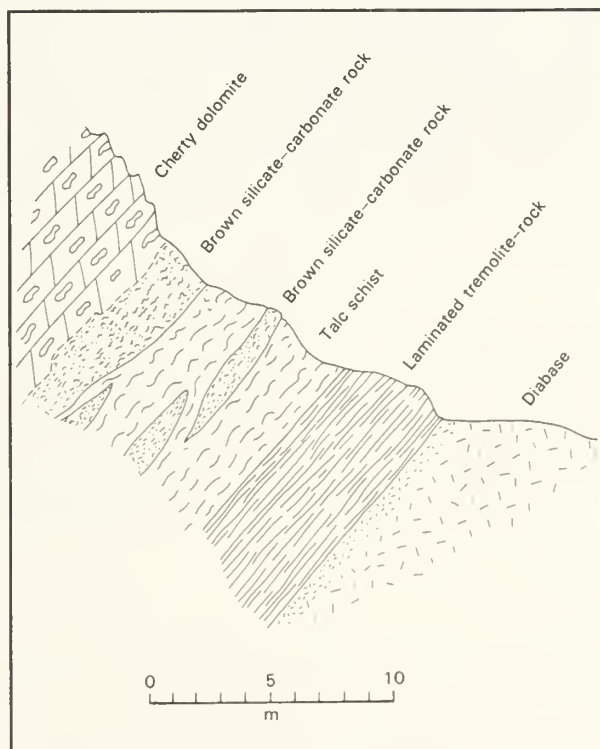


Figure 4. Diagrammatic cross section of a typical talc deposit in the Death Valley-Kingston area, California (after Wright, 1968, Figure 3).

and some lenticular limestone (Clark, 1964, Plate 1). Hydrothermal alteration of quartz-mica schist formed an ore body of steatite-grade talc (Taylor, 1989). Mesozoic plutonic rocks related to the Sierra Nevada Batholith are exposed within 2 km of the deposit and a high-angle northwest-trending fault, probably related to the Melones Fault Zone, is within one kilometer of the deposit (Clark, 1964, Plate 1).

## NEVADA

Most Nevada talc deposits are in the Palmetto and Sylvania districts in Esmeralda County (Papke, 1975). Although these districts are situated just across the state boundary from Inyo County, California, they are not contiguous with California talc districts (Figure 3). Most of the deposits in the Palmetto District are in the Harklin and Poleta formations of Early Cambrian. Individual deposits are controlled by moderately steeply dipping faults with a tendency for deposits to also be influenced by bedding.

The sedimentary host rocks in the Sylvania District are the Noonday Dolomite and Wyman Formation, both of Precambrian age. Intrusive granitic rocks of Jurassic age, which are abundant in this district, are separated from the sedimentary rocks by a moderate- to steep-dipping fault zone in the northwestern part of the district. Four deposits that contain both talc and chlorite situated along this fault probably accounted for 90 percent of production of talcose material from this district (Papke, 1975, p. 23).

Ore bodies in both districts are generally lenticular, but irregular in shape, as much as 180 m long and from 1 to 23 m thick. Talc contains some chlorite with quartz, calcite, dolomite, and less commonly sericite in low concentrations. The talc, which is very fine grained, consists of equant grains and is described as compact (Papke, 1975, p. 9).

## OREGON

Oregon talc deposits are in the northeast and southwest parts of the State (Figure 1) where accreted oceanic crust of Paleozoic and Mesozoic age contains serpentinite. In both areas faulting was important in the localization of at least some deposits. Jurassic plutons, ranging in composition from granite to quartz diorite, were important in generating hydrothermal fluids responsible for replacement of serpentine minerals by talc (Ferns and Ramp, 1988).

The largest deposits of amphibole-free talc are in the Sumpter area of northeastern Oregon, an area known for gold placers. Sumpter talc deposits are concentrated in a northwest-trending belt 8 km wide and 40 km long in the contact metamorphic aureole of the Late Jurassic Bald Mountain Batholith. Talcose rocks in this area that contain carbonates (dolomite or magnesite) do not contain

amphiboles. Tremolite or anthophyllite may occur if carbonates are present (Ferns, 1990). If there was sufficiently high concentration of  $\text{CO}_2$  in the fluids during talc formation, Ca and Mg were depleted by the formation of dolomite or magnesite and tremolite or anthophyllite did not form.

Talc deposits in southwestern Oregon also occur in Paleozoic and Mesozoic oceanic crust that was faulted and intruded by quartz dioritic Jurassic plutons. Soapstone for carving is quarried from the Elliott Creek Ridge deposit at the Pugh Mine. The deposit is within metamorphosed serpentinite surrounded by highly contorted gneissitic quartz-muscovite schists. Talc from this deposit contains chlorite, ankerite and some contains pyrite trace concentrations. In addition to the Elliott Creek Ridge deposit there are nine other talc deposits in southwestern Oregon, all of which were formed by hydrothermal alteration or metamorphism of serpentinite.

## WASHINGTON

There are at least 22 known talc occurrences in Washington; six in the Wenatchee area in the central part of the state, eight in Skagit County in northwestern Washington, and eight scattered around the eastern half of the state including one near Metalline Falls in the extreme northeastern corner of Washington (Valentine, 1960, Plate 38). Soapstone has been mined from deposits in Skagit County where talc replaced peridotite in a serpentinitized peridotite in the pre-Tertiary Skagit metamorphic suite (Misch, 1979). A deposit of talcose rock consisting of talc-tremolite schist near the small town Entiat in central Washington, is in a similar geological environment where talc replaced an ultramafic body in pre-Tertiary metamorphic terrain (McHugh, 1985; Talbot and others, 1980).

East of Metalline Falls fine-grained, white talc formed by the hydrothermal replacement of beds in the Moine Formation of the Proterozoic Windermere Group (Miller, 1982). Talcification may have been controlled by high-angle, northeast-trending faults in the vicinity of the deposit (Cordallis, personal communication, December 1992).

## MONTANA

Montana is the leading talc-producing state in the U.S. with production from three open-pit mines and one underground mine, all in the southwestern part of the State (Figure 5). In addition, chlorite is mined at an open-pit mine. Mine production in 1990 from Montana deposits was 430,125 mt of talc and chlorite (mainly talc) (Minarik and McCulloch, 1992, p.1). Markets for high-purity talc from these deposits include paper, paints, plastics, rubber, ceramics and cosmetics.



These talc and chlorite deposits occur in metamorphic rocks which are generally considered to be part of the Wyoming Province of Archean age and are exposed in the uplifted cores of block-faulted mountain ranges in southwestern Montana. Most--if not all--of these rocks were subjected to regional metamorphism of the amphibolite facies dated at 2,750 Ma ago (James and Hedge, 1980). Talc occurs in dolomitic marble within a metasedimentary sequence that also includes calcitic marble. Talc occurrences range from disseminated talc in low concentration marble and scattered masses only a few centimeters long, to a massive body 30 to 50 m thick and 360 m long at the Treasure Mine (Berg, 1979, p. 34).

Talc deposits occur in the Ruby, Greenhorn and Gravelly ranges and the Tobacco Root Mountains (Figure 5). Talc occurrences are numerous in the Ruby Range where there is one active open-pit mine, one active underground mine, and intermittent production from another open-pit mine. Ore bodies at these mines and also

at an inactive mine in the Greenhorn Range to the east are tabular and elongate parallel to lithologic layering in the metamorphic sequence. At all of these mines talc is developed in dolomitic marble near the contact with quartzofeldspathic gneiss or garnet-biotite schist. The more aluminous gneiss and schist have been altered to chlorite and sericite.

The greatest concentration of talc in Montana is in the Gravelly Range where large ore bodies are mined at the Yellowstone and Johnny Gulch mines. Probably as a result of isoclinal folding, dolomitic marble is exposed over an area 7 km long by 3 km wide; it is the largest exposure of dolomitic marble in southwestern Montana. Talc bodies in these deposits tend to be more lenticular than the tabular bodies in the Ruby Range (Figure 6). The main impurities are chlorite, which contributes to a darker color, and dolomite. Quartz occurs as a trace constituent in some talc. Talc from Montana generally is pale green to white, compact, massive and fine grained. However, talc--even from one deposit--shows considerable textural variation when examined by scanning electron microscopy (Berg, 1991).

It is generally assumed that the replacement of dolomitic marble by talc occurred during the Precambrian. Evidence for this assumption is that no known talc occurrences in Paleozoic sedimentary rocks, even though dolomitic beds of Paleozoic age occur in southwestern Montana. Unlike most of the western U.S. talc districts, igneous rocks are not associated with the talc deposits and structural control does not appear important in the localization of deposits. The most obvious control is lithologic; deposits are limited to dolomitic marble even though calcitic marble occurs within the sequence of metasedimentary rocks. Anderson, Mogk and Childs (1990) presented evidence of the volume for volume replacement of dolomite by talc and also for the replacement of calcite by dolomite. There is seemingly conclusive evidence for the introduction of Mg into these rocks as shown by the chloritization of rocks with low magnesium content, constant volume replacement of dolomite by talc as well as calcite by dolomite, and replacement of dolomite by magnesite. The source of the magnesium is not obvious nor is the source of the heat necessary for the development of hydrothermal fluids.

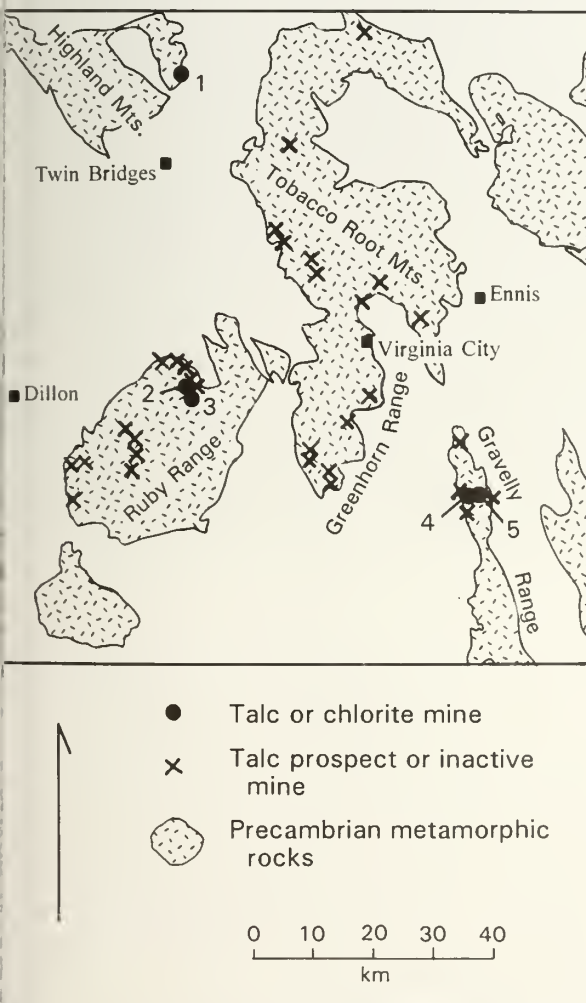


Figure 5. Talc mines and prospects in southwestern Montana. 1 - Antler Mine (chlorite), 2 - Treasure Mine (talc), 3 - Beaverhead Mine (talc), 4 - Johnny Gulch Mine (talc), and 5 - Yellowstone Mine (talc).



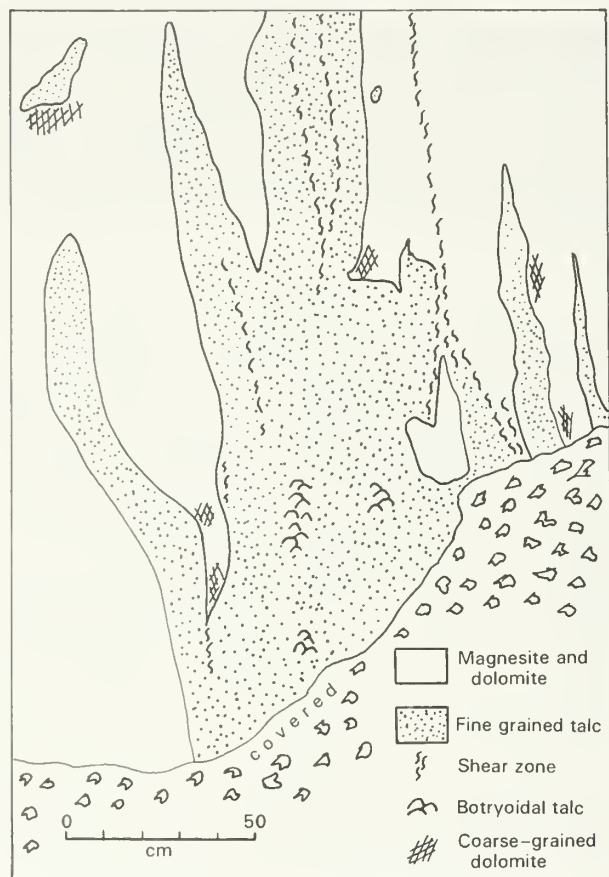


Figure 6. Sketch of talc exposed in cut in the Johnny Gulch area, Montana (Berg, 1979, Figure 21).

## OTHER WESTERN STATES

There are reported talc deposits in New Mexico and Wyoming, but apparently no recognized deposits of notable size in Arizona, Idaho or Utah. The Red Rock deposit is situated in the San Andres Mountains of south central New Mexico in the White Sands Missile Range (Fitzsimmons and Kelly, 1980). Talc was mined from this deposit between 1942 and 1945. This deposit is in Precambrian metamorphic rocks and may have formed by the replacement of carbonate or possibly quartz-chlorite phyllite. The orebody is 30 m long with a maximum width of 3.6 m, but averages 2.4 m in width.

In Sublette County, Wyoming pods of dark olive-green talc occur in schistose Precambrian metamorphic rocks (Harris, personal communication, December 1992). Plans are underway to quarry this talc for the carving market.

## COMPARISON OF GEOLOGY TO PHYSICAL PROPERTIES OF TALC

Western U.S. talc deposits formed by the alteration of ultramafic rocks and serpentinized ultramafic rocks (Llano, Texas; Oregon and Washington) as well as by replacement of carbonate sedimentary rocks by metamorphic, metamorphic-metasomatic, or hydrothermal processes (Allamore, Texas; California; Nevada and Montana). The precursor rocks were a major control on the talcose rock formed. As would be expected, talc rock formed by replacement of mafic and ultramafic rocks typically contains more iron than that formed by replacement of carbonate sedimentary rocks (Figure 7). Also, talc formed by the replacement of ultramafic rocks may contain a large concentration of chlorite and frequent carbonate minerals (Figure 8A). Massive varieties of typically dark green talc (soapstone) are well suited for carving small objects. This talc can also be used for so

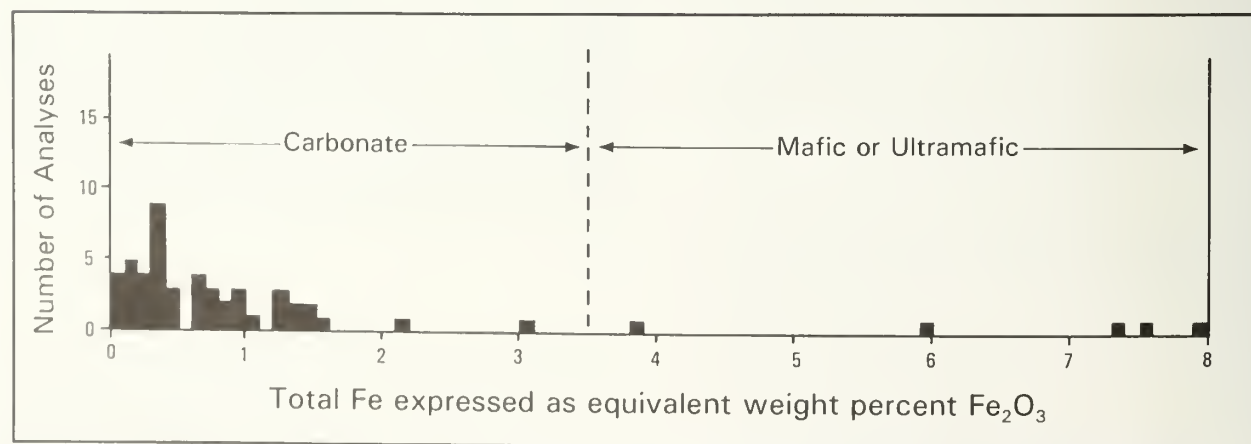


Figure 7. Iron content of some western U.S. talcs. Total iron expressed as  $\text{Fe}_2\text{O}_3$ . Analyses from Berg, 1979, Table 3; Bourbon, 1982, Table 1; Ferns and Ramp, 1988, Table 3; McHugh, 1985, Appendix B; Olson, 1976, Table 10-1; Page, 1951, Table 1; Papke, 1975, Table 3; Wright, 1954, Table 3; and Wright, 1968, Table 2.

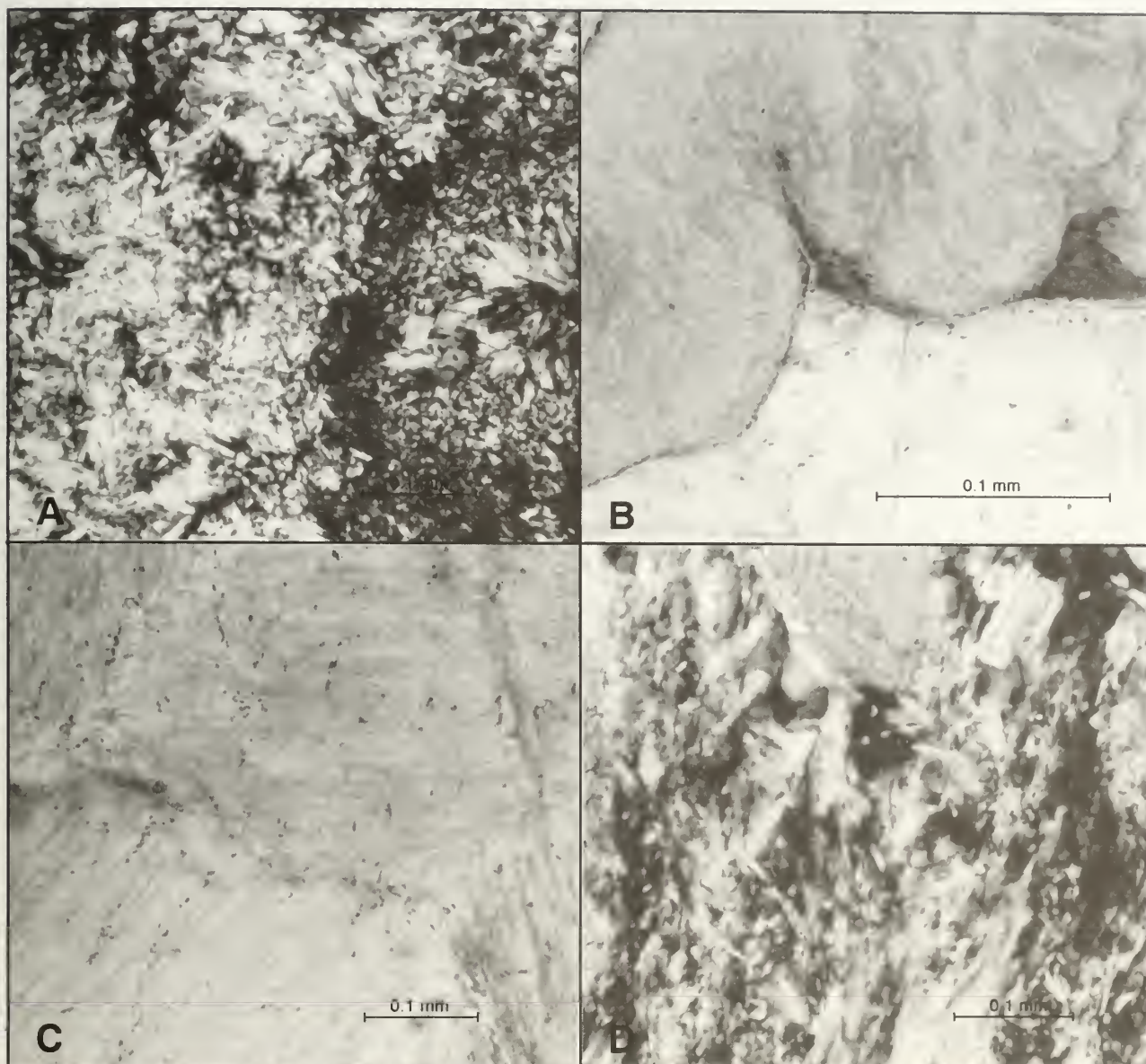


Figure 8. Photomicrographs of selected talc specimens from western U.S. deposits, all photographed with crossed nicols. A - Talc and chlorite, Marblemount, Skagit County, Washington; B - fine-grained botryoidal talc with late quartz, Johnny Gulch, Montana; C - talc after dolomite, Willow Creek Mine (inactive), Montana; D - Talc and dolomite, Allamore District, Texas.

the less demanding applications such as in roofing angles and insecticide carriers.

Talc formed by metamorphism and silication of carbonate beds is exemplified by the large deposits in the Death Valley-Kingston area and the Silver Lake area, both in southern California. Such deposits show large variation in mineralogy even within one deposit, ranging from fibrolitic talc (hard talc) to talc schist of high purity. Talc from these deposits was well suited for use as an extender in paint. It is a platy talc with high brightness which produces desirable properties in the paint. Tremolite tends to prevent settling of the pigment in the can and increases the durability of the paint. These talcs are also suitable for ceramic applications.

Hydrothermal talcs formed by replacement of carbonate beds (Inyo County, California; Nevada and Montana) are generally the purest talcs, and some are steatite grade (Figures 8B, 8C, and 9). Chlorite and dolomite in low concentration are typical impurities. These hydrothermal talcs are not generally foliated, but tend to be fine grained and massive. The high purity and lack of tremolite or significant carbonate as well as low iron content make these talcs suitable for many uses. In the past, massive steatite talc has been used for high frequency insulators, but new production methods have eliminated the need for block steatite for this use. However the small grain size and high purity of these talcs makes them well adapted for the production of micronized talc with an

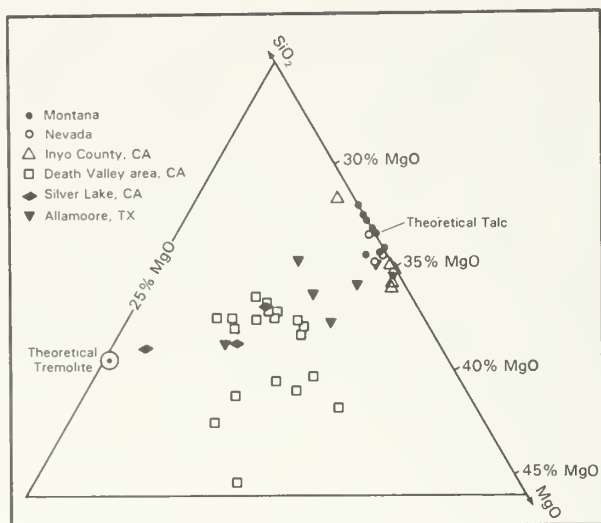


Figure 9. Ternary MgO-CaO-SiO<sub>2</sub> plot of compositions of western U.S. talcs formed by replacement of carbonate rocks. Analyses from same sources as those cited in Figure 7.

average particle size of less than 2  $\mu\text{m}$ . Such fine grained talcs find application in pitch control in paper and as functional fillers in plastics. Also because of their low iron contents these talcs can be used in ceramics. Talcs used in cosmetics must be platy enough to impart a slipperiness to the preparation as well as have high brightness and high purity. Some of the platier hydrothermal talcs meet the requirements for this demanding market. The black talc from the Allamoore District of Texas, although thought to be of hydrothermal origin, differs from other western U.S. hydrothermal talcs in containing not only carbonaceous material, but also carbonates (Figure 8D). The black carbonaceous material makes this talc unsuitable for those markets where brightness is an important consideration, but it is well suited for the manufacture of ceramic products.

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# 1992 Industrial Mineral Production in California and Nevada

by  
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## ABSTRACT

California was the leading state in industrial mineral production value with an estimated value of nearly \$2 billion. In total value of U.S. non-fuel mineral production estimated for 1992 by the U.S. Bureau of Mines, California ranked second; 81% of California's total production value was derived from industrial minerals.

California led all other states in the production of boron minerals, portland cement, diatomite, calcined gypsum and construction sand and gravel, and ranked second in potash and soda ash production. California's five leading industrial minerals in terms of value were portland cement, construction sand and gravel, boron, crushed stone, and soda ash.

California had 13 additional industrial minerals production with reported sales of over \$1 million including; industrial sand and gravel, magnesium compounds, lime, salt, potash, natural sodium sulfate, clay, feldspar, crude gypsum, pumice, dimension stone, calcium chloride and perlite.

## INTRODUCTION

Together, California and Nevada accounted for 84% of the nation's industrial minerals production in 1992. But there were big differences between the two states. California was the leading state in industrial mineral production with an estimated value of \$1,998,950,000, while Nevada ranked 30th among the states with an estimated value of \$240,030,000 for its industrial mineral production. California's mineral production was primarily industrial minerals; Nevada's mineral production is primarily precious metals.

In 1992 California ranked second and Nevada ranked third after Arizona (the leading state in the nation) in total value of U.S. non-fuel mineral production. However, 81% of California's total production value was derived from industrial minerals while only 10% of Nevada's total production value was derived from industrial minerals. Most of Nevada's mineral value came from precious metals. California, the leading state in the production of industrial minerals, was also the leading state in the production of boron minerals, portland cement, diatomite, calcined gypsum and construction sand and gravel.

## CALIFORNIA

### Portland Cement

Portland cement was the state's most valuable mineral commodity. Based on preliminary company reports, California's 1992 estimated production of portland cement was 9,145,000 short tons valued at \$548,700,000, about 5% more than that reported in 1991, although about 9% less than that of 1990. The diminished production in the last two years reflects the downturn of California's construction industry. Uses of cement by type of customer in 1992 were ready-mix concrete 72%; manufacturers of concrete products such as block, pipe, and prestressed precast concrete 12%; building material dealers 4%; highway contractors 5% and other contractors, government agencies and miscellaneous users 7%.

### Construction Sand & Gravel

Construction sand and gravel was California's second most important industrial mineral in terms of value. Reported production of 96,600,000 short tons valued at \$473,300,000 retained California's rank as the leading state in the production and value of construction sand and



gravel. Despite a drop of about 5% from last years estimated production--102 million short tons--which was attributed to the continuing two-year decline in construction in the state, mined output seemed to strengthen at year end and was expected to stabilize during 1993.

Sand and gravel pit operations continued to stir controversy throughout the state. Despite numerous complaints from citizens groups and neighbors of the adjoining pits, several sand and gravel operations received permits for expansions or new operations from city councils, county planning departments and county commissioners. Quality Rock Company received a permit to construct a new sand and gravel processing facility north of Moor Park's city limits in Ventura County. In March, Butte County board of supervisors approved the extension of the use permit of Green Rock quarries near Oroville. Syar Industries was allowed to continue mining gravel alongside the Russian River by a Sonoma County Superior Court in July. Tarmac California sold its aggregate operations in Riverside, Imperial and San Bernardino counties to Granite Construction Inc. in August. American Rock and Asphalt Inc. received clearance from Lake County to mine gravel along Putah Creek near Middletown. North Star Rock Products received approval in December for the proposed expansion of its Birchville Rock Quarry near Grass Valley. Granite Rock Company received approval from the San Benito County planning commissioners to use three canyons in the Anzar Hills as a dump for unusable mining waste.

The largest use of construction sand and gravel was as aggregate for the production of concrete (over the past several years this amount represented about 26% of California's total). Concrete is used in nearly all residential, commercial and industrial buildings and in most public works projects such as highways, bridges, dams, and sewer systems. The second largest use of construction sand and gravel (about 15%) is for base material in the construction and repair of highways, railways, and runways. Other major uses were as aggregate in paving highways, streets and parking lots (8%) and as fill in dams, (7%).

## **Boron**

California remained the sole source of domestic boron mineral production; it ranked as California's third most valuable mineral commodity. However, boron production was estimated to have dropped nearly 18% from 1,240,000 metric tons in 1991 to 1,020,000 metric tons in 1992; boron value also declined by about 25% to \$332,720,000. Production was principally from plants in Kern and San Bernardino counties. The U.S. Borax Company continued to be the largest producer of boron in the state, and the primary world supplier of sodium borates, (U.S. Borax is a part of Borax Consolidated Ltd. of the RTZ

Corp. PLC of London). Technical grade boric acid produced from U.S. Borax's extensive kernite ore deposits in Kern County for use in glass manufacture. Glass products consumed 62% of the current boron production, soaps and detergents 9%, fire retardants 5% and other 24% (fertilizer, protective coating for steel, glazing ceramic tiles).

## **Crushed Stone**

On the basis of tonnage, the crushed stone industry is the largest nonfuel mineral industry in the United States and exhibited a 4.8% increase over reported production in 1991. California ranked twelfth among the states in total tonnage of crushed stone produced in 1992 and eleventh in total value. Stone production is surveyed by the Bureau of Mines for odd-numbered years only and 1992 data is based on estimates by Bureau specialists. Estimated crushed stone production in 1992 was 41,200,000 short tons and valued at more than \$200,000,000; it was California's fourth most valuable industrial commodity. Principal uses for California crushed stone were in cement manufacture, concrete and bituminous aggregate and road base.

California is the largest producer of crushed trap rock which is produced mainly in the Northeast and Pacific Coast states. Crushed sandstone, quartzite and volcanic cinders are also produced in California. More than 100 operations were reported producing from over 270 quarries in 1991. About the same number were estimated to be in production in 1992. Some of the larger producers included Beasar West Inc., Southdown Inc./Southwest Portland Cement Co., Syar Industries Inc., Granite Rock Company, and CalMat Co.

## **Soda Ash**

Soda ash, the commercial term for sodium carbonate, was California's fifth most valued industrial mineral produced in 1992. The U.S. soda ash industry is composed of 6 companies, 5 in Wyoming and 1 in California. U.S. production of natural soda ash from Wyoming and California reached a record 9.5 million tons in 1992, valued at better than 800 million dollars, most of which came from Wyoming, but a considerable amount was produced in California.

The former Kerr-McGee Chemical facility at Searles Lake, California (California's sole producer) was sold in November 1991 to North American Chemical Company. In addition to the soda ash produced at its Argus plant, North American Chemical continued to produce various boron, potassium and sodium products from its Trona and Westend plants on Searles Lake. Plans were announced during the year to increase annual production capacity by about 545,000 tons beginning in the second half of 1995.

Lake Minerals Corporation (a subsidiary of Cominco, ) and Volcan Chemicals of Birmingham, Alabama ed together to form the Owens Lake Soda Ash Com- y. Owens Lake announced the beginning of permit- g for a \$150 million soda ash mining project expected begin operation in 1995. Plant construction is sched- d to begin at the 600,000 tons-per-year soda ash plant ate 1993. The project draws from the dry Owen Lake l in Inyo County and is expected to employ about 90 t-time employees.

Sodium bicarbonate, sodium sulfate, potassium chlo- e, potassium sulfate and borax were produced as products from sodium carbonate production in Cali- nia. The reported distribution of soda ash by end use luded: glass, 48%; chemicals, 24%; soap and deter- ts, 13%; flue gas desulfurization, 3%; pulp and paper, , water treatment and other 4%.

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Clays were another important industrial mineral com- dity in California reporting over 2 million metric tons ed with an estimated value of more than \$78 million. mmon clay and shale comprised the bulk of the clays cessed, but higher valued bentonite, fuller's earth and olin production accounted for more than 60% of the ue of California's clay production. Principal clay uses re in brick making, portland cement, ceramics, pet ste, absorbents and in structural concrete.

The Amador County Board of Supervisors approved e permits for North American Refractories Co.'s new y mine and tile manufacturing plant in the Carbondale a, 6 miles northwest of Ione. The process will include ing, crushing and screening the clay, forming it into pes for floor and roof tiles and baking the tiles in a gas d kiln.

### Other Industrial Mineral Commodities

Reported sales of better than \$1 million were also de for 13 additional California commodities. In order value, they included industrial sand and gravel, mag- sium compounds, lime, salt, potash, natural sodium fate, clay, feldspar, crude gypsum, pumice, dimension ne, calcium chloride and perlite. Lesser valued indus- al minerals in California included asbestos, barite, ca, talc, fuller's earth, and masonry cement.

## NEVADA

In Nevada, construction sand and gravel was the st valuable industrial mineral commodity, followed in scending order by portland cement, diatomite, lime, ium, gypsum and clay. Four additional Nevada indus- al mineral commodities reported sales of over \$1 mil- n; crushed stone, mined magnesite, barite, and fuller's th. Nevada was the leading state in the production of

barite and mined magnesite and ranked second in lithium and diatomite production. Lesser valued commodities produced in 1992 were salt, perlite and industrial sand and gravel (silica sand).

### Construction Sand and Gravel

Construction sand and gravel production increased in Nevada during 1992 despite a downturn in Clark County (Las Vegas) construction that lasted from 1990 (which was an all time high) into the latter part of 1992. But construction--particularly large casino and govern- ment projects--began to pick up in the second half of the year and sand and gravel production responded. Nevada's construction sand and gravel production in 1992 was reported to be 20,700,000 short tons, valued at more than \$71 million. The amount was up 3% from the 1991 estimate, and up 13% from the 1990 reported record high of 18,377 short tons. (The U.S. Bureau of Mines only collects sand and gravel production data on even num- bered years). The urban counties of Clark and Washoe provided most of the total.

Major producers of construction sand and gravel were within two highly urbanized counties; Clark County, that includes Las Vegas, and Washoe County, that in- cludes Reno. The major producers within Clark County included Bonanza Materials Inc., Beazer USA, Nevada Ready Mix Corp., Las Vegas Paving Corp. and Southern Nevada Paving. Granite Construction Co. was the largest sand and gravel producer in Washoe County.

### Portland Cement

Portland cement production ranked second among Nevada's industrial mineral production value for 1992. Although it was not as large as that of 1990, it was greater in both quantity and value than that of 1991. The Nevada Cement Co. plant at Fernley, about 30 miles east of Reno, produces about 400,000 tons of portland cement per year, according to the Nevada Bureau of Mines and Geology. An extensive upgrading program began in 1991 and sales were expected to increase because of a substan- tial duty recently imposed on Japanese cement imports. Construction was nearly completed at the Las Vegas Cement Co. Inc. plant at Logandale in Clark County, when a major explosion delayed the opening. They hoped to begin production in 1993.

### Diatomite

Nevada's 1992 diatomite production was 9% higher than in 1991 and its reported value ranked it third among the states industrial minerals. Eagle-Picher Industries Inc. with mines in northern Nevada was the state's largest producer. Its Storey County plant produced diatomite for filtration, insulation and filler uses. Absorbent and filler grade material was also produced in Churchill and Esmeralda counties.

# NONFUEL MINERAL PRODUCTION IN CALIFORNIA<sup>1</sup>

Mineral	1991		1992		1993 <sup>*</sup>	
	Quantity	Value (thousands)	Quantity	Value (thousands)	Quantity	Value (thousands)
Asbestos metric tons	W	W	10,998	\$4,452	12,000	\$4,800
Boron minerals						
thousand metric tons	1,240	\$442,531	1,009	338,700	526	323,870
Cement (portland)						
thousand short tons	*8,702	*522,120	8,035	428,016	8,698	463,339
Clays:						
Bentonite thousand metric tons	147	12,885	143	13,069	141	13,312
Common do.	1,815	9,714	1,635	8,146	3,120	17,110
Kaolin do.	113	4,865	128	4,958	39	1,045
Gemstones	NA	10,450	NA	9,916	NA	1,046
Gold <sup>2</sup> kilograms	30,404	355,125	33,335	369,723	32,400	369,797
Lime thousand short tons	307	20,389	280	18,072	317	20,459
Mercury metric tons	( <sup>3</sup> )	1	( <sup>3</sup> )	( <sup>3</sup> )	( <sup>3</sup> )	( <sup>3</sup> )
Pumice do.	61,237	4,372	W	W	W	W
Rare-earth metal concentrates do.	16,465	W	20,699	W	20,000	W
Sand and gravel:						
Constructionthousand short tons	*101,900	*489,100	112,888	522,108	103,500	476,100
Industrial do.	2,104	41,690	2,096	42,396	1,921	36,723
Silver <sup>2</sup> metric tons	W	W	18	2,259	17	2,296
Stone:						
Crushed thousand short tons	45,816	216,156	*40,800	*198,300	42,400	207,800
Dimension short tons	44,757	5,254	*23,292	*4,148	29,140	5,547
Combined value of calcium chloride (natural) <sup>4</sup> , cement (masonry), clays (fuller's earth), copper (1991), diatomite, feldspar, gypsum (crude), iron ore (usable), magnesium compounds, mica [crude (1991)], molybdenum (1991-92), perlite, potash, salt, soda ash, sodium sulfate (natural), talc and pyrophyllite, titanium concentrates (ilmenite), tungsten, and values indicated by symbol W	XX	403,592	XX	381,575	XX	338,343
Total	XX	2,538,244	XX	2,345,838	XX	2,281,587

<sup>\*</sup>Estimated. NA Not available. W Withheld to avoid disclosing company proprietary data; value included with "Combined value" data. XX Not applicable.

<sup>1</sup>Production as measured by mine shipments, sales, or marketable production (including consumption by producers).

<sup>2</sup>Recoverable content of ores, etc.

<sup>3</sup>Less than 1/2 unit.

<sup>4</sup>Discontinued beginning 1993.



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Lime production was Nevada's fourth most valuable industrial commodity last year. Nevada's lime production, which was principally used by the gold mining industry, continued to rise in both tonnage and value, up about 14% from 1991. Chemstar Inc. produced dolomitic lime at Henderson from dolomite mined at Sloan, south Las Vegas and high calcium lime at Apex, to the north Las Vegas. Continental Lime Inc. supplied the mining industry with lime from its Pilot Peak operation near Henderson in Elko County.

## Lithium

Lithium carbonate was the fifth most valuable industrial mineral produced in Nevada during 1992. Cyprus General Company pumps brine from beneath a dry lake near Silver Peak in Esmeralda County into a 4,000-acre solar evaporating pond system. Estimated consumption of U.S. lithium compounds declined about 15% in 1992 and this amount was reflected in a 35% drop in Nevada's lithium production. The use of lithium compounds in ceramics, glass and primary aluminum production represented more than 60% of estimated domestic consumption. Other major end uses for lithium were in the manufacture of lubricants and greases and synthetic rubber production.

## Gypsum

The U.S. remained the world's leading producer of gypsum, accounting for 15% of the world's total output. Among the 20 U.S. producing states, California ranked first and Nevada sixth, both producing more than 1 million tons each. A year end spurt in Las Vegas construction was expected to propel Nevada's gypsum production above 1991's decline, which dipped because of decreased construction. The domestic gypsum industry is dominated by a few large vertically integrated companies that mine and calcine gypsum and manufacture plaster and wallboard products. Small amounts of very pure gypsum are used as filters and in glass making, paper making and pharmaceutical applications. Uncalcined gypsum is marketed for use in portland cement, agriculture and filters. Over 60% of the uncalcined gypsum is used in portland cement and the remainder is used mainly for agricultural purposes. Most of Nevada's gypsum is produced in Clark County, but U.S. Gypsum produced from its Empire Mine in Pershing County, and 1992 production was also from Clark County by Art Wilson Co. Las Vegas producers included James Hardie Gypsum, Pacific Coast Building Products Inc. and Georgia Pacific. The Nevada Department of Minerals reported production of 1,400,000 short tons in 1992.

## Crushed Stone

Nevada's crushed stone production was also expected to increase in 1992 following the passage of the Surface Transportation Assistance Act of 1991. Crushed stone production is surveyed by the U.S. Bureau of Mines for odd-numbered years only. So, the 1992 crushed stone production was based on an estimate by the Washington Commodity Specialist. The projected increases were expected to be influenced by construction activity primarily in the public construction sector. Nine companies reported crushed and broken stone production in Nevada in 1991; the three leading companies were Centex Corp.'s Nevada Cement Company, Southern Nevada Liteweight Co. and Chemstar Inc. The 1991 production was 1,200,000 short tons, valued at better than \$6.5 million. Projections indicate that despite drops in southern Nevada's housing construction, crushed stone production in 1992 increased 8% to 1,300,000 metric tons and was valued at \$7.3 million. Major uses for crushed stone were for concrete aggregate, unpaved road surface, cement manufacture and agricultural uses. Crushed limestone, dolomite, granite, volcanic cinders and traprock were reported from seven counties.

## Barite

About 88% of the nation's barite production in 1992 came from Nevada, the leading U.S. barite producing state. Nearly 90% of the barite sold in the U.S. was used as a weighting agent in oil and gas drilling fluids, mostly in the Gulf of Mexico and in the Pacific Coast areas. Nevada mines, crushers and grinders are competitive with foreign imports in the California market. Barite was also used in the production of paint, rubber, glass and barium chemicals. About 340,000 tons of barite was reported by the Nevada Department of Minerals to be shipped from Nevada for oil and gas drilling.

## Magnesium

Magnesium oxide and other compounds were recovered from seawater by five companies in California, Delaware, Florida and Texas. Two California-based companies mined magnesite near Gabbs Nevada; Marine Maganium Co. of San Francisco, and National Refractories & Minerals Corp. of Moss Landing. Total U.S. demand for magnesium compounds increased slightly in 1992, and the demand pattern also changed. Nonrefractory applications of magnesia gained a greater share of the total demand at the expense of refractories. Producers were developing new magnesium compounds in environmental applications. Dead-burned magnesia refractories used in bricks for metal, cement and glass production

furnaces continued to be the primary application for magnesium compounds. Chemical processing was the next largest segment. Magnesia is used to remove sulfur from flue gases and boiler tubs, and is used for acid neutralization to process waste water. Both California and Nevada produce magnesium compounds. California from seawater and Nevada from mined magnesite.

## CONCLUSION

Although the final 1992 tabulations have not been completed for some of California's and Nevada's industrial minerals, all-in-all it was a good year for mineral producers. If the predicted recovery in construction materializes, 1993 should show increases in most industrial mineral commodities production value, particularly Nevada. Despite the sluggishness of California's economy in 1992, industrial mineral sales appeared to dip only slightly (less than 1%) and were increasing at year end. Possible increases in highway and public spending projects in the coming year could also result in an increase in 1993's production value.

# Limestones of New Mexico and Adjoining Areas Suitable for Sulfur Removal in Coal-Fired Power Plants

By

Frank E. Kottlowski<sup>1</sup> and Augustus K. Armstrong<sup>1</sup>

## ABSTRACT

Widespread high-calcium (HC) limestones in New Mexico and adjoining areas, are low in magnesium, but some units include shale interbeds that would be deleterious for usage in sulfur removal. In southwest New Mexico, southeast Arizona, and adjoining parts of Mexico, limestones in the thick Mississippian Escabrosa, Pennsylvanian-Permian Horquilla, and Cretaceous U-Bar units are HC as are strata in the Mississippian Lake Valley, Pennsylvanian formations, Permian Hueco, and parts of the Permian Capitan Limestone of south-central and southeast New Mexico and west Texas.

In north-central and central New Mexico, many limestones in the Pennsylvanian Madera Formation are HC as are some of the Cenozoic travertines. In northwest New Mexico, where the present-day mine-mouth coal-fired power plants occur, there are no HC limestones, but to the north in southwest Colorado some beds of the Mississippian Leadville Limestone and Pennsylvanian Hermosa Formations are HC.

HC limestones considered contain at least 95 percent calcium carbonate and less than 3 to 5 percent magnesium carbonate. Limits for other impurities are alumina, 1 percent; silica, 2 percent; sulfur 0.05 percent; phosphorous, 0.02 percent; and iron oxide, about 1 percent. Chemical and physical requirements differ slightly depending upon the ultimate use.

## INTRODUCTION

Reconnaissance sampling of HC limestones in New Mexico has been reported by Siemers (1982), Jicha (1956), and Kottlowski (1962). There are numerous articles describing the limestone units in and near the state, such as Armstrong (1958) for west-central New Mexico, Mississippian and Pennsylvanian Systems in the state (Armstrong, and others, 1979), Pennsylvanian units in south-central New Mexico (Wilson, 1989), Pennsylvanian strata in southwest New Mexico and southeast Arizona (Kottlowski, 1960), Pennsylvanian section in Big Hachet Mountains (Thompson and Jacka, 1981), Paleozoic strata in Big Hachet Mountains (Zeller, 1965), Mississippian in southwest New Mexico and southeast Arizona (Armstrong, 1962, 1988), Mississippian in San Juan Mountains (Armstrong, 1978), Mississippian and Pennsylvanian rocks in Sangre de Cristo Mountains (Berthland, 1963), Pennsylvanian System in New Mexico

(Bachman, 1975), Pennsylvanian and Wolfcampian rocks in southeast New Mexico (Meyer, 1966), Paleozoic rocks in Manzano Mountains (Myers, 1973), and Paleozoic strata in the Sacramento Mountains (Pray, 1961). Other shorter articles report on Paleozoic outcrops of individual quadrangles, and numerous reports detail the thick Permian strata in southeast New Mexico in the Guadalupe Mountains; many of these carbonate rocks are dolomite or dolomitic

HC limestones best serve for usage in sulfur removal, either directly or converted to lime. The latter is an important basic chemical utilized also in production of glass, paper, alkalies, metallurgical flux, calcium carbide and for water purification plants. The copper smelters in southwest New Mexico are heavy users of lime for flux. HC limestone may meet the requirements of dimension stone and can be used as crushed stone for aggregate, to make cement, and as "lime" for soil conditioning although less pure limestone can be quarried for these purposes.



HC limestone contains at least 95 percent calcium carbonate (about 53.22 percent CaO) and less than 3 to 5 percent magnesium carbonate; limits for other impurities are alumina, 1 percent; silica, 2 percent; sulfur, 0.05 percent; phosphorous, 0.02 percent; and iron oxide, about 1 percent. The chemical and physical requirements differ slightly depending upon the ultimate use.

Quick and hydrated lime, obtained by calcination of HC limestone, are low cost, flammable, perishable products. Safe transportation is expensive and, with the low price of the bulk material, makes shipping over long distances uneconomical. New Mexico, with only two large metropolitan centers (Albuquerque and El Paso) in or close to the state and a relatively sparse number of industries, is unfavorably located for a large usage of chemical- and industrial-grade lime, except for cement plants. However, the lack of a lime-producing plant in New Mexico has resulted in long-distance shipping from Arizona to a power plant in the Four-Corners region of northwest New Mexico.

### USAGE FOR FLUE-GAS DESULFURIZATION

The Clean Air Act of 1990 established requirements for electric utilities requiring SO<sub>2</sub> emissions to be halved by flue-gas cleaning systems and fuel modifications. These apply to all power plants even those fired by low-sulfur (1 percent or less sulfur) coal. Using limestone in scrubber systems can remove 95 percent of the sulfur, and lime (CaO) can remove 98 percent. General estimates are that to remove 1 ton of sulfur takes 4 tons of limestone and can result in 14 tons of waste material. In regions where landfill sites are costly (perhaps as much as \$250,000 per acre), production of byproduct gypsum may be a financial alternative to throwaway solid waste (Ellison and Kantze, 1993).

Most limestone used for scrubbers should be 93 to 96 percent calcium carbonate, with less than 3 to 6 percent magnesium carbonate, and free of fluorine, selenium, and mercury.

New Mexico has numerous large deposits of gypsum (Weber and Kottowski, 1959), therefore flue-gas desulfurization byproduct gypsum, mainly to produce gypsum board and portland cement, probably is not competitive.

There are three large coal-fueled power plants in New Mexico. Two are in the northwest corner of the state, west of Farmington, the Arizona Public Service Co. Four Corners Plant and the Public Service Co. of New Mexico San Juan Plant. The Escalante Plant of Plains Electric Coop. is in west-central New Mexico, between Grants and Gallup.

The Four Corners Plant, can produce 2,269 megawatts of electricity, and uses about 8,500,000 tons of coal per year from the adjoining Navajo Mine of BHP-Utah International Inc., with the coal averaging about 8,700 Btu/pound, 0.78 percent sulfur, and 22.2 percent ash. To handle their sulfur emissions, they buy lime from a plant near Tucson, Arizona, ship it by railroad to Gallup, New Mexico, then haul the lime in trucks to the power plant. The waste from the scrubbers is thickened to almost solid calcium sulfite, fly ash added, then trucked to the Navajo Mine and deposited in the stripped pits.

The San Juan Plant, is rated at 1,710 megawatts, uses about 6,000,000 tons of coal from the adjoining San Juan Mine and the nearby La Plata Mine, both operated by BHP-Utah International, Inc., with the coal containing about 9,540 Btu/pound, 0.74 percent sulfur, and 23 percent ash. They truck soda ash from Wyoming to use in their scrubbers and produce sulfuric acid. Waste ash is placed in the San Juan Mine stripped pits.

The Escalante Plant, rated at 235 megawatts, uses about 890,000 tons of coal from the Lee Ranch Mine of Santa Fe Pacific Coal Corp., shipping the coal by rail. The coal yields about 9,420 Btu/pound, 0.7 percent sulfur and 15.7 percent ash. They buy limestone (Permian, New Andres Limestone) from a quarry on the southwest side of the Zuni Mountains, truck it to the plant, add it to the scrubber system; the waste sludge, calcium sulfite is placed in a landfill, and covered by soil and vegetation. They utilize all the ash by shipping it by railroad and truck to the Tijeras cement plant of Holnam, Inc. east of Albuquerque.

In eastern Arizona, three power plants near the New Mexico border are supplied with New Mexico coal. These are the Cholla Plant of Arizona Public Service Co. at Joseph City, the Coronado Plant of Salt River Project near St. Johns, and the Apache Station Plant of Arizona Electric Power Corp. near Cochise.

### DISTRIBUTION OF LIMESTONES

Limestones crop out or are near the surface in about one fourth of the state; they range in age from the Precambrian dolomitic limestone lenses in the Cambrian part of the Bliss Sandstone to the Cenozoic travertine, calcarenite, tufa, and caliche. Some of the HC limestones of Mississippian, Pennsylvanian, Permian, and Early Cretaceous exceed 100 feet, and locally even 1000 feet, in thickness. The purity ranges from almost pure calcite to the calcareous tufa and caliche which in places contain as much as 40 percent insoluble residues. Locating outcrops of HC limestone is no problem, but the most economical deposits should fulfill three requirements: (1) be easily mined by open-pit methods; i.e., should cap extensive mesas and underlie thin overburden; (2) be within 20 miles of a

road and accessible by good trucking roads; and (3) be within short distance of a gas pipeline. The intersections of highways, railroads, and gas pipelines with limestone outcrop area determined most of the deposits investigated. Some limestones in relatively inaccessible areas were sampled to obtain a fairly complete stratigraphic coverage of limestones in the State.

Limestones checked and sampled as possible economic HC deposits include Cenozoic travertine of the Cerro Mesa, Mesa del Oro, and Ladron Mountains areas; the caliche "caprock" of the Llano Estacado; the Tertiary caliche limestone of Apache Valley; limestone beds in the northern and central New Mexico Upper Cretaceous sequence; the Lower Cretaceous limestones of southwest New Mexico; the Jurassic Todilto limestone southeast of Grants and east of Santa Rosa; favorable Permian, Pennsylvanian, Mississippian limestones in the Robledo, Guadalupe, Sacramento, Peloncillo, Florida, Tres Hermanas, Oscura, Sandia, Manzano, Sangre de Cristo, Ladron, and Magdalena mountains, Border Hills, Cerros de Amado, and near Luna; and the El Paso Limestone in the Victorio Mountains. The samples collected are merely partial testing off the limestones in these areas and are only a rough guide to commercial possibilities.

### Pre-Mississippian Limestone

Small lenses of carbonate rocks, dolomitic in most places, occur amid rocks of Precambrian Age in widely scattered points of southern New Mexico, such as in the redrock area and near Hembrillo Canyon in the central San Andres Mountains. The thick Precambrian quartzite and schist sequences of the central and northern parts of the State lack appreciable amounts of limestone.

Fossiliferous pre-Mississippian post-Precambrian strata crop out only in southwest and south-central New Mexico, the northeasternmost outcrops being in the northern San Andres and southern Oscura mountains. The oldest unit is the Bliss Sandstone, of Cambrian and Ordovician Ages; locally, there are a few limy beds near the top of the sandstone, *sensu stricto*. The overlying El Paso and Montoya formations of Ordovician Age, are chiefly of dolomite and magnesium limestone. The El Paso Limestone may contain some local HC limestone beds; it thickens, under a pre-Montoya erosion surface, to a knife-edge at the northern sections (in the northern San Andres Mountains) to more than 1400 feet near El Paso, being about 800 feet thick in the latitudes of Las Cruces and Deming. Analyses of the El Paso Group limestones from scattered localities (Kottlowski, 1957) show more than 10 percent magnesium carbonate, and in most samples at least 5 to 10 percent insoluble residues, chiefly of quartz silt. Selected limestones from the El Paso limestone in the Victorio Mountains, however, contain most 94 percent calcium carbonate.

Except for a few beds of impure limestone in the upper Cutter Formation, the Montoya Dolomite is entirely of dolomite or dolomitic limestone (except for basal dolomitic sandstones), although locally there are beds of magnesium limestone. Limestones have been reported in the Montoya from the Cooks Peak and other areas; several such beds contain more than 5 percent magnesium carbonate.

The Silurian Fusselman Dolomite is more than 800 feet thick in the triangular area from the Victorio Mountains southeastward to the Franklin Mountains, but it thins rapidly northward and westward as a result of erosion during early Devonian and/or late Silurian time. Some of its carbonate-rock beds are as calcic as dolomitic limestone, but all its units appear to be high in magnesium (Kottlowski, 1957) with dolomite dominating. Devonian rocks typically are calcareous shales and calcareous siltstones; the only limestone beds are impure, thin, and lenticular. Silty dolomites, however, occur in the Onate Formation. Pre-Mississippian limestones are not likely sources of HC lime in New Mexico.

### Mississippian Limestones

Mississippian strata in northern and central New Mexico occur as discontinuous remnant outcrops beneath an erosion surface of late Mississippian and early Pennsylvanian Ages (Armstrong, 1955, 1958). Some of the crinoidal calcarenites in the Sandia, Ladron, Magdalena, Nacimiento, and Sangre de Cristo mountains appear to be relatively HC limestone except for sparse to abundant chert lenses and nodules. Locally, these encrinurites are thick (20 to 50 feet) and cap low benches below ledges and slopes eroded on the shaly lower Pennsylvanian strata. Samples from cherty Mississippian limestones near Bishop's Lodge (Kottlowski, 1962) in the southwestern Sangre de Cristo Mountains and along Las Huertas Creek Canyon in the northeastern Sandia Mountains contained only 91 percent calcium carbonate, 2 to 6 percent magnesium carbonate, and 1.5 to 5.6 percent silica. These samples are representative of the total thickness of the Mississippian limestones at these localities; selected purer samples had insoluble residues (quartz and clay) of 0.3 to 0.7 percent. In the southeastern Sangre de Cristo Mountains along Gallinas Canyon east of Montezuma, as reported by Baltz and Read (1960), the Cowles Member of the Tererro Formation (upper unit of the Mississippian) is as much as 40 feet thick and consists of a crinoidal calcarenite with insoluble residue (grab sample) of about 0.6 percent.

The Mississippian Lake Valley Formation exceeds 100 feet in thickness in the Sacramento Mountains (Pray, 1961), southern San Andres Mountains (Kottlowski and others, 1956), Cooks Peak-Lake Valley area (Jicha, 1954), and Silver City-Santa Rita district. Similar limestones,



partly correlative with the Lake Valley Formation, are placed in the Escabrosa Group by Armstrong (1962). This group includes as much as a 1000 feet of carbonate rocks in the Big Hatchet and Animas mountains (Figure 1) and Klondike Hills, and locally it may exceed 500 feet in the Peloncillo and Tres Hermanas mountains. Analyses of these crinoidal strata show them to be HC. Near Alamogordo millions of tons are available within a short distance of a gas line and railroad.

The Mississippian strata in the Franklin Mountains are mainly siliceous impure limestone of the Rancheria Formation. To the north along the Rio Grande, the Mississippian section is thin or absent in the Robledo and Caballo mountains.

### Pennsylvanian Limestones

The sedimentary beds of Pennsylvanian Age are thick, if variable, in New Mexico (Thompson, 1942; Kottowski, 1960; Read and Wood, 1947; Armstrong, and others, 1979) and crop out in most of the major mountain ranges. The majority of the outcrops include HC limestones, and in many areas these limestones underlie dip-slope mesas where they could be quarried from open pits with removal of only thin overburden. Extensive outcrops of Pennsylvanian limestones occur in the Sangre de Cristo, Nacimiento, Sandia, Manzano, Los Pinos, Ladron, Magdalena, Oscura, San Andres, Sacramento, Franklin, Robledo, Big Hatchet, and Peloncillo mountains, the Cerro de Amado, and the Silver City-Santa Rita area. Smaller outcrop areas are scattered in many other mountain ranges. An average section (if there is one) of the Pennsylvanian strata is 1000 to 3000 feet thick and consists of a basal clastic unit in which most of the limestones are arenaceous, a thick medial unit of cherty to HC limestones, and an upper unit of interbedded marine limestones and shale-sandstones beds (i.e., siliciclastic beds). The medial unit forms ledgy cliffs in many mountain ranges. Dip slopes of the tilted fault-block ranges are, in many places, of massive limestones in the upper unit. Obviously, the best quarry locations (such as the Tijeras Cement Plant east of Albuquerque) are within HC limestones of the middle Pennsylvanian, where the interbedded, shaly, clastic strata have been removed by erosion, leaving thick, pure limestones near the surface covered by only thin overburden. Such possible quarry locations occur in most of the mountain ranges listed.

### Permian Limestones

The basal Permian strata in many parts of south-central New Mexico are the interbedded red beds and marine limestones of the Bursum Formation (Wilpolt and Wanek, 1952; Thompson, 1954). Southward from the Oscura Mountains, this formation and correlative units include some massive HC limestones that are near trans-

portation facilities in the northern Sacramento Mountains (Otte, 1959) and Robledo Mountains (Kottlow, 1960). The upper part of the Horquilla Limestone, hundred of feet of massive limestone, is of early Permian in the Big Hatchet (Zeller, 1958) and Peloncillo mountains.

The basal Permian in most of north-central New Mexico is within the Abo Redbeds, the Sangre de Cristo Formation, or the Cutler Redbeds. The Abo Redbeds grade southward into the Hueco Formation which includes thick, HC limestones in the San Andres (Kottlov and others, 1956), Franklin (Harbour, 1960), Robledo, Dona Ana (Kottowski 1960), Florida, and Tres Hermanas mountains.

The Yeso Formation, conformable on the Abo Redbeds, consists of interbedded gypsum, brown sandstone, pinkish shale, and thin, impure limestone. The amount of limestone, as well as the thickness of the limestone unit, increases southward. In most areas, however, the Yeso limestones appear to be dolomitic and silty. Outcrops of the Yeso Formation may locally contain HC limestone. In the central part of the State, the Yeso is overlain by the Glorieta Sandstone and in turn by the San Andres Limestone. In south-central New Mexico, however, the Yeso grades up into the San Andres Limestone with several thin, lenticular, arenaceous beds in the upper Yeso or lower San Andres being called the "Glorieta" or Horquilla Sandstone.

The San Andres Limestone (and uppermost beds of the Yeso) crops out over extensive areas in the central, south-central, and southeast parts of the State. The formation is the surface bedrock of Chupadera and Juma mesas, the higher mesas east of Socorro and on the southeast back slope of the Los Pinos Mountains; the western plateau (on the west edge of the High Plains) extends south from near Vaughn onto the east back slopes of the Jicarilla, Capitan, White, and Sacramento mountains and much of the Otero Mesa-western Guadalupe Mountains area of southeastern Otero County. The San Andres Limestone caps dip-slope cuestas or hogback ridges bordering the Zuni, Nacimiento, Sandia, San Andres, Cristobal, and Caballo mountains, Lucero Mesa, Sieber Cuchillo, and the Phillips Hills. The formation crops out on the Glorieta Mesa escarpment and occurs in small outcrop patches along Nogal Canyon in the volcanic Sacramento Mountains and on the south side of Horse Mountain amid the volcanic rocks of the Datil Plateau.

Descriptions of the carbonate-rock beds of the San Andres Limestone show most individual beds to be dolomitic limestone or magnesium limestone (i.e., more than 5 percent magnesium carbonate). Beds quarried near Gallinas in central New Mexico, for example, show (Vincent C. Kelley, written communication, 1957) 20





percent magnesium oxide, 32.20 percent lime, and 3.26 percent silica. In the central Guadalupe Mountains, Boyd (1958, p. 24) reported that samples typical of the San Andres Formation contained 1.1 to 0.5 percent silica, 40.6 to 45.7 percent magnesium carbonate, and 53.1 to 58.8 percent calcium carbonate—nearly pure dolomites! In contrast, however, samples from the type section of the San Andres Limestone, in Rhodes Canyon of the San Andres Mountains, gave (Kottlowski, 1957) analyses high (13.2 percent) in silica (quartz sand and silt) for the basal 95 feet of dolomitic limestones, but an average lime content of 53.5 percent for the overlying 220 feet (insoluble residue 1.3 percent) of relatively pure limestones, whereas the upper 255 feet of the formation contains 20.3 to 28.7 percent magnesium carbonate. On the eastern slopes of the Sacramento Mountains, and in oil tests drilled in that area, the lower part of the San Andres Limestone is reported as chiefly limestone, whereas the upper beds are mainly dolomite. Extensive sampling of the widespread San Andres Limestone outcrops should locate some HC limestones in places where they could be quarried economically.

Northward from the type section (Lee and Girty, 1909; Needham and Bates, 1943; Kottlowski and others, 1956), the San Andres Limestone thins from the 600 to 750 feet in the northern San Andres Mountains to 110 feet in the southeast Zuni Mountains (Figure 2) and 15 feet on northern Glorieta Mesa. Interbeds of gypsum occur in such areas as Mesa del Oro (Jicha, 1958), Lucero Mesa (Kelley and Wood, 1946), and southeast Chupadera Mesa (Wilpolt and Wanek, 1952), suggesting deposition in nearshore lagoonal evaporite basins. Toward the southeast, the San Andres Limestone apparently thickens in the Guadalupe Mountains to about 1200 feet (Hayes, 1959) locally, although there is considerable disagreement as to formation boundaries (Boyd, 1958) and as to the carbonate rocks included within the San Andres Limestone. Triassic or younger strata overlie eroded parts of the San Andres Limestone where it is present in the state, except in the eastern part where the Guadalupian Bernal Formation or Artesia Group rests upon the San Andres Limestone.

The interbedded red beds, gypsum, and dolomitic rocks of the Artesia-Bernal Group (Formation) crop out along the Pecos River Valley from Carlsbad northward, and in the Guadalupe Mountains. The carbonate-rock beds are thin, lenticular, impure, and dolomitic. Correlative basinal beds of the Cherry Canyon and Bell Canyon formations crop out in the state only along the New Mexico-Texas stateline in the southern Guadalupe Mountains. The limestone members of these formations locally are as much as 100 feet thick. The carbonate rocks of the Cherry Canyon Formation are impure or dolomitic (King 1948, Newell and others, 1953); the Rader and Lamar

Limestone Members of the Bell Canyon Formation, however, include HC limestones (Kottlowski, 1962) that crop out on the southeast side of the Guadalupe Mountains. The basinal Yezo equivalent, the Bone Spring Limestone crops out in the Brokeoff Mountains, the western part of the Guadalupe Mountains, a relatively inaccessible area. Analyses from King (1948) of the upper part of the Victorio Peak Member of the Bone Spring Limestone show that it is a HC limestone.

The massive Capitan reef limestone crops out along the southeast Guadalupe Mountains escarpment from Carlsbad and is 1500 to 2000 feet thick if measured vertically and is 1500 to 2000 feet thick if measured vertically without regard to the dip of the reef-flank beds. The limestone, according to Newell and others (1953) is mainly of unstratified calcitic limestone, whereas the bordering reef-talus beds contain high percentages of dolomite. They listed 11 analyses of the Capitan reef limestone which average 98.2 percent calcium carbonate, 1.3 percent magnesium carbonate, and 0.4 percent silica. Obviously, this appears to be a huge mass of HC limestone near gas fields, a railroad, and U. S. highways. Much of the outcrop area is within Carlsbad Caverns National Park but the outcrop belt extends for about 10 miles north of the Park, and from the Park southwestward to the New Mexico-Texas stateline. cursory sampling of the Capitan Limestone however, suggests the limestone and dolomite facies are complexly mingled. Whereas most of the reef-flank beds appear to be dolomitic, or at least magnesium-rich, some of the reef-core beds also contain appreciable amounts of magnesium carbonate. A chip-channel sample (Kottlowski, 1962) of the reef core in Dark Canyon yielded 16 percent magnesium carbonate. Where the reef-core facies is overlain by sandstone tongues of the Yates and Tansill Formations, the core appears to be dolomitic and siliceous, as along North Slaughter Canyon. Also, along parts of McKittrick, Rattlesnake, and West Slaughter canyons, the reef-flank beds, especially the more massive ones, appear to be chiefly limestone (determined by dilute HCl and by specific gravity tests with heavy liquids).

The Ochoan Castile and Rustler Formations crop out above the Guadalupian rocks in the Delaware basin forming low hills between the valleys of Black River and the Pecos River south of Carlsbad. The Rustler Formation is dolomite, gypsum, and siltstone, whereas the underlying Castile Formation outcrops consist of gypsum interlaminated gypsum and limestone, and some thin beds of limestone. In the subsurface, both formations include much anhydrite and some halite. Oddly enough, an analysis of basal limestone from the Castile Formation as given by King (1948), shows a HC limestone containing 96.63 percent calcium carbonate. Most of the Castile limestones are too thin and too intimately interlaminated with gypsum to be of commercial use.



Figure 2. Map of northwestern New Mexico showing limestone outcrops.



In the southwestern corner of New Mexico, Permian rocks younger than the Hueco Formation crop out in the Big Hatchet, Peloncillo, and Animas mountains. The section, as described in detail by Zeller (1958) consists of the Horquilla Limestone (of Pennsylvanian and Wolfcampian Ages), Earp Redbeds, Colina Limestone, Epitaph Dolomite, Scherrer Sandstone, and Concha Limestone. Fusulinids date the upper Horquilla as Wolfcampian and the Concha Limestone as Leonardian. Yochelson (1956) identified Wolfcampian gastropods in the Colina Limestone from southeast Arizona; the upper Horquilla Limestone, Earp Redbeds, and the overlying Colina Limestone appear to be a sequence similar to that in the Robledo Mountains (Kottlowski, 1960) where the Hueco Limestone includes a tongue of the Abo Redbeds. Both the Horquilla and Colina Limestone probably contain HC limestone beds but crop out in relatively inaccessible areas. A chip-channel sample from the Colina Limestone in the Peloncillo Mountains (Kottlowski, 1962) showed large amounts of silica and magnesium carbonate, but the sample was collected in a metamorphosed zone near a granite intrusive mass.

The Epitaph Dolomite includes gypsum and siltstone interbeds and may be a southwestern correlative of the Yeso and Bone Spring Formations; no appreciable amount of HC limestone is known from the Epitaph Dolomite. Likewise, the Concha Limestone appears, from the scant data available, to be too cherty and too dolomitic to contain high-calcium limestones.

### Mesozoic Limestones

Limestones in Triassic rocks are limited to thin, lenticular, arenaceous to conglomeratic, limy beds in the Chinle and Moenkopi Formations of northwest New Mexico and the Dockum/Chinle Group of the eastern part of the State.

Within Jurassic strata, limestones occur in the Todilto Formation of northern New Mexico. Where typically developed, this formation consists of a lower limestone and an upper gypsum; locally, the limestone is as much as 40 feet thick. The limestone is dark, laminated, thin- to massive-bedded, fetid, and contains upper laminae of gypsum. Near the western edge of limestone deposition, in Todilto Park close to the New Mexico-Arizona stateline, the limestone grades laterally from a 14-foot limestone bed into limy sandstone and siltstone. North of Todilto Park near Beautiful Mountain, Allen and Balk (1954) noted an extensive mesa capped by 7 to 14 feet of Todilto limestone and estimated the reserves at 36 million tons. These samples average 12.27 percent silica. Allen believed the silica is present as an arenaceous laminate within the lower foot of the limestone. He suggested that if this lower foot were selectively left in quarrying, the upper beds would be a HC limestone averaging 97.5 percent calcium carbonate.

The Todilto limestone crops out along the north edge of the Zuni Mountains from near Wingate to east Grants. The limestone is 7 to 30 feet thick in this area (average thickness of about 14 feet) with numerous laminae of sandstone, siltstone, and gypsum – as well as pods of uranium ore. Farther to the southeast, the Todilto limestone crops out along the north valley wall of Rio Jose from near Mesita to north of Suwanee and in several isolated outcrops of the flanks of Mesa Redonda and Lucero Mesa. Thicknesses range from 5 to 16 feet. Similar thicknesses occur northeast of Acoma.

Along the north wall of the broad valley of Arroyo Colorado, the Todilto limestone is thick and caps extensive benches extending from Mesita southeast to Petate Butte which is near its southwest wedge-edge. Silberman (1948) reported local thicknesses of 40 feet. A chip-channel sample contained about 94.3 percent calcium carbonate; selective mining may yield a HC limestone.

East of the Rio Grande Valley there are small patches and some, more extensive, outcrops of the Todilto Formation northeast and east of the Sandia Mountains, near Lamy and near Rosario siding, and south of Galisteo. The limestone member is thin (3 to 8 feet thick) and impure. Steeply dipping beds of the Todilto Formation occur along the west side of Sierra Nacimiento south of Chama southward to White Mesa near San Ysidro; here the limestone member, a thin-bedded shaly unit, is 6 to 10 feet thick and is overlain by interlaminated limestone and gypsum that grade up into the thick, massive gypsum member (Weber and Kottlowski, 1959). The Todilto limestone is exposed north of Gallina in a northwest structural extension of the hogback ridges near Cuba as well as to the east along the canyon of Rio Chama and to the south of its tributaries, Rio Puerco and El Rito. Outcrops of the Todilto Formation encircle Mesa Prieta in this Rio Chama area; the limestone member is lenticular, ranging from 10 to 18 feet in thickness, and consists of lower dark shaly grading upward from thin-bedded gray limestone to massive gray limestone. This in turn grades up into the gypsum member. Typically, the Todilto caps benches above cliffs of the Entrada Sandstone and below slopes cut in the Morrison Formation.

The Todilto limestone crops out in the hogback ridges along the southeast edge of the Sangre de Cristo Mountains near Las Vegas but is thin. On the south edge of Louisiana Mesa near the west border of Quay County east of Ima (sec. 18, T. 8 N., R. 27 E.), the eastern pinchout of the Todilto limestone borders the valley of Alamogordo Creek. The limestone is 2 to 10 feet thick and is a thin, laminated, platy to fissile bed containing paper-thin laminae of siltstone and gypsum. Amazingly, however, a chip-channel sample shows almost 95 percent calcium carbonate with only slightly more than 1 percent silica. The Todilto limestone crops out as a ledge, capping the slopes

own to light-gray Wingate Sandstone, and is overlain by the slope-forming shales and sandstones of the Morrison Formation.

Cretaceous strata in New Mexico change abruptly in the sandstone-shale-coal of northern and central New Mexico, which is chiefly of Late Cretaceous Age, southward to the marine limestones, cobble conglomerates, and reddish clastic rocks of southwest New Mexico, which are mainly of Early Cretaceous Age. Limy beds of the Dakota Sandstone occur within the Mancos Shale, Mesaverde Group, and Lewis Shale in northwestern New Mexico, Mancos Shale in central New Mexico, and Graneros Shale, Greenhorn Limestone, Carlile Shale, Niobrara Formation, and Pierre Shale of the northeast part of the State. These formations tend to contain more limestones, and thicker limestones, as one goes from the west to the northeast.

Along the west edge of the San Juan Basin, limy beds of the Cretaceous are thin, argillaceous limestone lenses in concretionary strata in the lower part of the Mancos Shale or in the Lewis Shale (Beaumont, 1954, 1955; Allen and Balk, 1954). In the Gallup-Zuni Basin, a 10-foot-thick bed of fossiliferous impure limestone occurs at the base of the Mancos. Eastward into the Mount Taylor region and to the southeast edge of the San Juan Basin, the limy beds are only calcareous, fossiliferous sandstone and zones of limestone concretions. Along the northeast edge of the San Juan Basin, and in the eastward adjoining Chama basin, equivalents of the Graneros, Greenhorn, Carlile, and Niobrara are recognized (Dane, 1960, 1968). The Greenhorn Limestone member of the Mancos Shale consists of interbedded, gray, dense limestone and dark-gray calcareous shale; the limestone beds (units) are as much as 2½ feet thick (Dane, 1960) and are described as a limonitic *Globigerina* biomicrite by Wehlberger and others (1960). Dane (1960) also noted the thin, gray, shaly limestones in the Niobrara calcareous shale member. Obviously, none of the Cretaceous limestones of northwestern New Mexico are HC limestone. Burchard (1913) reported a lime kiln active near El Estland; limy lenses in the Lewis Shale were quarried for this operation, as well as coquina oyster beds at the top of the Pictured Cliffs Sandstone.

In northeast New Mexico, limestones occur as thin, impure beds in the Graneros, Carlile, and Pierre Shales, and in the Greenhorn Limestone and Fort Hays Limestone.

Scattered areas of Cretaceous rocks crop out in southern Santa Fe County and the adjoining eastern parts of Sandoval and Bernalillo counties; however, the Greenhorn Limestone is merely interbedded limestone (in beds

6 to 12 inches thick) and shale, and the Niobrara Formation appears to be comprised entirely of clastic rocks. Similarly, only thin, impure limestones occur in the Cretaceous of the Carthage coal field (Wilpolt and Wanek, 1952), Caballo Mountains (Kelley and Silver, 1952), southern San Andres Mountains (Kottowski and others, 1956), Cooks Range (Jicha, 1954), and Silver City area. Near the Capitan coal field in south-central Lincoln County on the east side of the Sierra Blanca volcanic complex, there is a 60-foot-thick sequence of dark-gray limestone in the lower part of the Mancos Shale. Shale interbeds make up much of the sequence, and the limestone beds are impure.

Cretaceous strata near the Mexican border include thick fossiliferous limestones, chiefly of Early Cretaceous Age. These Cretaceous limestones, and interbedded clastic units such as limestone-cobble conglomerate, sandstone, and tuff-breccia, range from hundred to thousands of feet in thickness in the East Potrillo (Bowers, 1960), Big Hatchet (Zeller, 1965), Little Hatchet, Animas, Peloncillo and Victorio mountains, and form small areas of outcrop on Cerro del Muleros, on the west edge of the West Potrillo Mountains, and in faulted areas of Sierra Rica and the Apache Hills. Large masses of relatively HC Cretaceous limestone are in remote localities, except the somewhat marly beds that encircle Cerro de Muleros near El Paso. The limestone used by the Southwestern Portland Cement Company from quarries near Cerro del Muleros is almost HC limestone, being barely too high in silica (3.2 percent) and with considerable magnesium carbonate (2.1 percent). Higher, thick-bedded limestone from the Buda Formation, collected on the outskirts of Sunland Park Village, is similar in composition containing several percent too much silica (3.7 percent) and clay (alumina 0.7 percent).

The thick, Early Cretaceous limestone section in the East Potrillo Mountains probably contains some HC limestone. It is 25 miles west of El Paso, reached by good ranch roads. A sample of the marbleized Early Cretaceous limestones along the fault zone at the base of section shows much silica and alumina, about 10 percent combined. These lower limestones are overlain by 400 to 600 feet of intercalated limestone cobble conglomerate, arenaceous limestone, and limy sandstone; above is 200 to 500 feet of massive fossiliferous reefoidal limestone. These massive limestones, however, cap the range and may be costly to quarry.

The section of Early Cretaceous rocks near the Cornudas Mountains, along the center of the southern border of Otero County is chiefly of clastic beds with only a minor amount of sandy and shaly limestone.



## Cenozoic Limestones

Most of the Cenozoic sedimentary strata of New Mexico are of clastic rocks which are highly calcareous because of their derivation, in part, from pre-Cenozoic limestones. The distinct "limestones" in the Cenozoic are classified as follows: (1) fresh-water lacustrine limestones, (2) spring deposits, calcareous tufa, and travertine, and (3) caliche blankets. Except for a few exceptions, these nonmarine calcium carbonate deposits do not qualify as HC limestone because of their high content of clay and noncarbonate-rock sand and silt. Impure limestones occur in many of the Tertiary sedimentary units. For example, there are thin beds (several inches thick) and laminae of tuffaceous limestone and limy tuff within the basal Tertiary of Robledo Mountains, a unit of interbedded red siltstones, gypsum, and tuff. Travertine and calcareous tufa spring deposits are extensive in the state: some of the larger deposits are those around Lucero Mesa and Mesa del Oro. The banded porous travertine of the northeast Lucero Mesa area has been quarried as travertine "marble" and makes an attractive ornamental stone. Jicha (1956) described similar spring deposits from the Mesa del Oro area and gave an analysis showing the calcium carbonate content as 96.5 percent. The three samples that he combined for the analyses yielded insoluble residues of 0.3, 1.3, and 3.0 percent.

The travertine deposits on the northeast end of Lucero Mesa near South Garcia station were sampled extensively; only a few samples gave less than 10 percent insoluble residues, and these higher grade travertines were from thin lenticular beds. A representative chip-channel sample of a 17-foot-thick "bed" (Kottlowski, 1962) shows about 85 percent calcium carbonate, 11 percent silica and alumina, and almost 1 percent combined iron oxide and sulfur.

West of the Ladron Mountains, and overlooking Rio Salado to the south, massive-bedded and laminated travertine caps the Santa Fe Group and older beds, occurring along a north-south belt about 3 miles wide and about 9 miles long, underlying about 20 square miles of upland plains. A chip-channel sample of the laminated limestone shows 99 percent calcium carbonate. Grab samples from other localities contain scattered to abundant grains of quartz silt.

The banded travertine deposits described by Jicha (1956) at the northern tip of Mesa del Oro occur in a rather anomalous situation for spring deposits. They cap the easily eroded Triassic red beds high above valleys carved in the red beds, and locally are overlain by Quaternary basalt flows. Apparently they are not related to any faults. Being erosional remnants, their original extent is not known, but they form continuous north-south belt about 5 miles long and 2 miles wide. About 7 to 10 miles

to the northeast of Mesa del Oro, and 1 to 5 miles west of Lucero Mesa, high, isolated buttes are capped by are small remnants of similar travertine. If these travertine deposits were a single continuous sheet during the Tertiary, they covered an area of at least 35 square miles and may be playa lake deposits, or relatively pure caliche capping an old erosion surface.

Several lenticular (reefoid?) algal limestones, local in lenses as much as 40 feet thick, occur in the Tertiary Palm Park Formation of the southwestern Caballo Mountains. In the valleys of Apache and Green Creeks, the Palm Park Formation, about 900 feet thick, is unconformable on Paleozoic rocks and consists of three units: (1) a basal one third of interbedded red siltstones and pebbly boulder conglomerates with clasts of Precambrian Paleozoic rocks as well as of andesitic lavas, (2) a middle one third of light blue-gray to purple porphyritic limestone tuff, and (3) an upper one third of pinkish tuffaceous sandstones and lenticular algal limestones. The mottled like masses of algal limestone appear to be high in calcium carbonate, with one chip-channel sample of a 40-foot-thick lens yielding 97 percent calcium carbonate.

Caliche is widely used for road metal in the intermontane plateaus and the High Plains parts of the State, but in those areas the only monolithologic calcium-carbonate rock inexpensively available. Finely banded (algal-laminated) and pisolitic travertine lenses occur in many localities in the caliche, especially in the "caprock" of the High Plains in eastern New Mexico. As described by Bretz and Horberg (1949), the typical caliche profile (developed on limestone-pebble gravels), in descending order consists of (1) dense, banded to structureless caprock, (2) less dense brecciated caprock, (3) chalky caliche with concretionary nodules, (4) impure caliche with cupped pebbles, and (5) slightly leached and coated precaliche limestone gravel. In most areas the relatively pure "limestone" is thin, 1 to 2 feet, and lenticular. Bretz and Horberg reported an average of only 3 percent insoluble residues from 12 samples of the "caprock" caliche. Sampling of the top 2½ zones (banded caprock, brecciated caprock, and upper chalky concretionary caliche) from three widely separated localities in southeastern New Mexico gave an average insoluble residue of more than 31 percent. Selected fragments of the upper caprock may contain only three to ten percent insoluble residues, but any appreciable thickness or lateral mass of the caprock appears to be high in siliceous impurities.

Thick (thicker than 2 feet), extensive, and relatively pure caliche appears confined, except for localized deposits, to surfaces bordering the valley of the Rio Grande and its tributaries and to the Llano Estacado of eastern New Mexico and its isolated western remnants. The caliche of eastern New Mexico is more important economically as it provides road metal and aggregate for the part of the state.



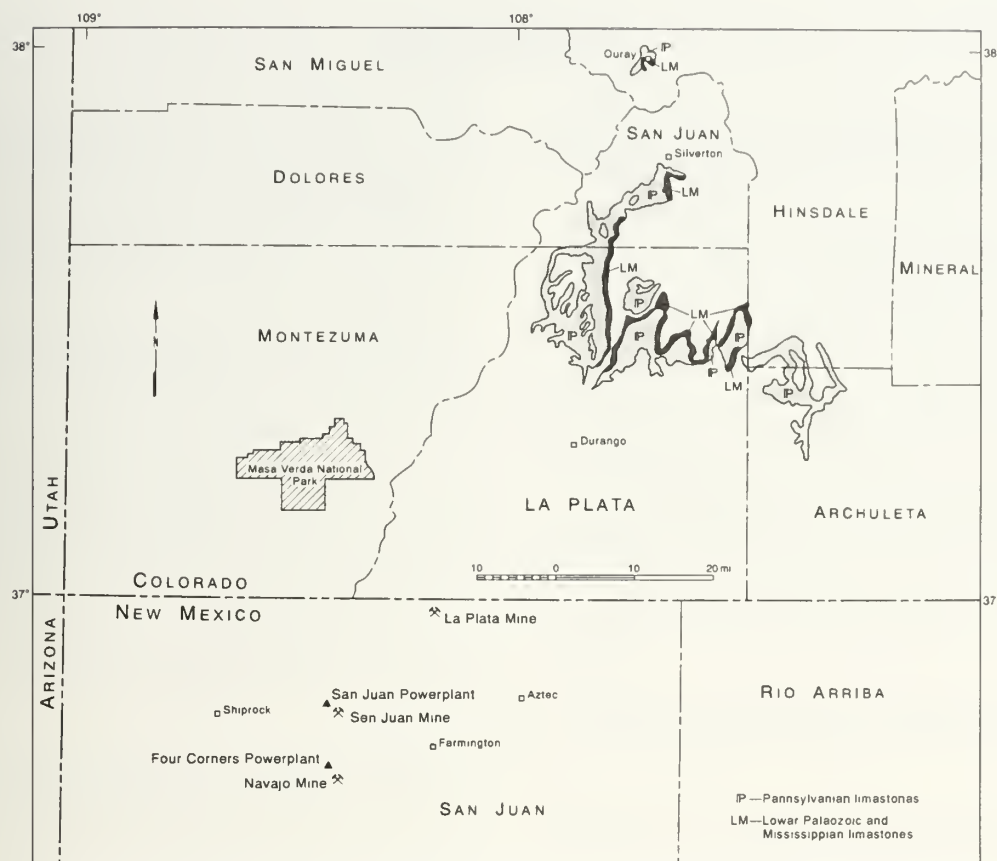


Figure 3. Map of southwestern Colorado and northwestern New Mexico showing limestone outcrops.

Local pods of the caprock caliche, as reported by Bretz and Horbert (1949), may be HC "limestone," but these high-purity masses are erratic and discontinuous and do not appear to be of economic significance other than for use as road metal.

### SAN JUAN MOUNTAINS, SOUTHWEST COLORADO

The San Juan Mountains (Figure 3) are a dissected range more than 100 miles across. The mountains are primarily of Tertiary volcanic rocks, but in the western and northern parts bodies of Paleozoic rocks are exposed. The Paleozoic limestone outcrops bordering the Animas River are some 60 to 70 miles northeast of the Four Corners power plants. The Cambrian Ignacio Quartzite (10-150 feet thick) rest unconformable on Proterozoic rocks. The Devonian Elbert Formation (20-70 feet thick) is composed of calcareous shales and thin sandy limestones with salt casts. The Devonian Ouray Limestone (10-200 feet thick) is a relatively pure, massive limestone. The Mississippian Leadville Limestone (100-150 feet thick) is composed of crinoidal limestones and dolomitic limestones.

The Pennsylvanian Hermosa Formation is a 2000-foot-thick series of alternating limestones, shales, siltstones and conglomerates. The limestones are generally massive, of marine origin and commonly contain bituminous matter. Limestone beds range from ten to 50 feet in thickness.

Although the limestones along the Animas River north of Durango are the closest carbonate rocks to the two power plants west of Farmington, it is doubtful that they could be utilized because the outcrop areas are environmentally sensitive forest lands. The transportation highway goes through the scenic tourist city of Durango, and in many places the highway would be dangerous with constant traffic of large trucks.

### CONCLUSIONS

New Mexico has ample amounts of HC limestone but no large quantities near the two present-day power plants west of Farmington. The Escalante power plant in west-central New Mexico does use Permian limestones for its flue-gas desulfurization.

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# Mineral Land Classification in California

by

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## ABSTRACT

One of the principal responsibilities of the California State Geologist is to provide local governments with maps and information regarding mineral resource occurrences within their jurisdiction. The primary objective of this effort is to furnish basic data that is essential in planning for and accommodating wise development of mineral deposits that are important to the economic well-being of the region, state, and nation. Local government agencies are required by law to incorporate the information provided by the State Geologist into their general plans and formulate mineral resource management policies that emphasize conservation and development of mineral deposits.

The Mineral Land Classification program was initiated by the State Geologist in 1977 under authority of the California Surface Mining and Reclamation Act (SMARA). To date, about 33,000 square miles of land have been classified for mineral resource potential. Most of the mineral land mapping has been conducted in three principal areas: (1) metropolitan areas of the state where urban encroachment has greatly diminished available supplies of construction aggregate; (2) Sierra Nevada foothills, a region that is undergoing dramatic population increases; and (3) the Mojave Desert and Great Basin regions, where large Federal land withdrawals are pending that could preclude mining.

Mineral land classification studies address the overall mineral potential of a region through the identification of local and regional geologic factors that control or influence the formation of mineral deposits. These studies are field-intensive surveys that enable project geologists to gain first-hand knowledge about the nature and distribution of mineral deposits in a given area and portray that information accurately in map form.

This paper summarizes the progress made in the Mineral Land Classification program in the metropolitan, Sierra Nevada foothills, and the Mojave Desert/Great Basin regions of California. Selected projects from each area are discussed in detail.

## INTRODUCTION

California is well known for its abundant and diverse mineral resources. They resulted from natural processes that have taken place within the vast period of California's geologic evolution, which began approximately 1.8 billion years ago (oldest radiometrically dated rocks in California).

## HISTORY

As far back as 12,000 years ago, Native Californians used mineral resources for their daily needs. They quarried obsidian for points, scrapers, and knives, and talc and soapstone for pipes, bowls, beads, and pendants. They obtained pigments from hematite, limonite, manganese, cinnabar, and chalk, and chipped chert, jasper, agate, chalcedony, petrified wood, and quartz crystals

into points, knives, and drills. They made jewelry, charms, pigments, and ceremonial items from manganese, turquoise, chrysocolla, tourmaline, galena, alabaster, and other minerals. They also used many types of rock, including granite, pumice, sandstone, and slate, for mortars, pestles, metates, blades, and other tools, and mined salt to season and preserve food (Heizer and Treganza, 1944; California Department of Conservation, 1993).

Cabrillo's coastal voyage in 1542 marked the beginning of Spanish, English, and Russian exploration and use of California's resources. Settlements grew after the establishment of the first Spanish mission by Junipero Serra in the San Diego area in 1769. The Missionary Period, which lasted into the 1830s, saw an increase in the use of

mineral resources, especially the nonmetals (the "industrial minerals") such as clay, gypsum, stone, sand, and gravel, for construction of the missions. Demand for mineral resources increased steadily as new settlements were established by those who arrived by ship during the early 1800s, as well as by pioneers who migrated overland from the east, beginning with the arrival of the Bidwell-Bartleson Party in 1841.

California's population had already grown substantially, and urban and agrarian communities had developed by the time the news of the 1848 discovery of gold on the American River reached San Francisco and beyond. The California Gold Rush followed, as well as increasing numbers of prospectors and new settlers. By the time California attained statehood in 1850, there was considerable demand for metallic as well as nonmetallic mineral resources. By the early 1940s the dollar value of the nonmetallic mineral resources produced in California began to increase steadily at a rate clearly exceeding that of the metals, a trend that has continued to the present. The dollar value of California's nonmetallic minerals currently produced is about four times the value of the metallic resources.

Research conducted around the turn of the century by renowned economic geologist Waldemar Lindgren, and subsequent work by others, shows that mineral resources are associated with particular rock types or suites of rocks in distinct and often unique geologic settings. This provides a convenient and informative basis for evaluating them according to their genetic type or mode of origin. The plate tectonic theory developed during the mid-1960s led to current understanding of the formation, evolution, and composition of the earth's crust. With this knowledge, geologists can more confidently identify geologic terranes where economic mineral resources are most likely to be found.

## MINERAL COMMODITIES AND USES

Mineral resources are commonly separated into two categories, metallic and non-metallic. The latter are often referred to as industrial minerals. Metals include base metals-- such as copper, lead, and zinc--as well as precious metals such as gold, silver, and platinum. Industrial minerals include limestone, clay, gypsum, sand and gravel, boron minerals, volcanic cinders, rare-earth minerals, sodium and potassium compounds, specialty sands, talc, garnet, crushed stone, diatomite, dimension stone, and many others.

Some mineral commodities, metals for example, be economically mined and transported to markets worldwide. Marketability of other mineral resources, sand and gravel for instance, is dependent on transport distance--cost doubling each 40 to 50 miles (64 to 80 km) transport by truck.

An average of 40,000 pounds (14,930 kg) of mineral resources are used annually for each American. At this level of consumption, according to Lasman (1992), the average child will need a lifetime supply

800 pounds (300 kg) lead  
750 pounds (280 kg) zinc  
1,500 pounds (560 kg) copper  
3,590 pounds (1,340 kg) aluminum  
32,700 pounds (12,200 kg) iron  
26,550 pounds (9,900 kg) clay  
28,210 pounds (10,530 kg) salt  
1,238,100 pounds (462,100 kg) stone, sand, gravel, and cement

The mining industry furnishes the majority of the materials used in construction of homes. According to the California Mineral Education Foundation (1993), the average American home contains:

120,528 pounds (44,986 kg) concrete  
15,300 pounds (5,711 kg) concrete block  
21,440 pounds (8,002 kg) brick  
14,218 pounds (5,307 kg) gypsum wallboard  
376 pounds (140 kg) asphalt felt  
366 pounds (125 kg) aluminum siding  
843 pounds (315 kg) plaster  
779 pounds (291 kg) insulation  
501 pounds (187 kg) copper pipe and wiring  
210 pounds (78 kg) ceramic sinks and toilets  
405 pounds (151 kg) sheet metal ducts  
1,010 pounds (377 kg) appliances  
290 pounds (108 kg) vinyl flooring  
54,000 pounds (20,155 kg) sand, gravel, and stone  
268 pounds (100 kg) glazing (glass)  
20,000 pounds (7,465 kg) other mineral products.

Because we have become accustomed to using great quantities of mineral resources, our well-being and standard of living are largely dependent on our ability to find, mine, process, transport, and use mineral resources economically.



## CALIFORNIA'S MINERAL RESOURCES

There are about 80 non-fuel minerals known to have been commercially available at one time or another within the state. About 35 mineral commodities are presently mined in California (Burnett, 1993). Principal minerals include aggregate, carbonate rock, borate minerals, rare-earth minerals, diatomite, gypsum, asbestos, magnesium and sodium compounds, calcium chloride, specialty and common clays, specialty sand, and gold. The estimated value of California's 1992 mineral production is about 2.5 billion dollars, 80 percent of which was from industrial minerals production.

### Mining in California

There are about 1,100 active mines in California, the largest group being construction aggregate, followed by other industrial minerals, and finally metals (Rapp and others, 1990). These mines are in 57 of the 58 counties. California law requires that mines and related activities having significant impact on the environment operate under conditional use permits that include approved mining and reclamation plans. Permits for projects taking place on non-federal land are coordinated and processed by the city or county government that has local authority. For most proposed mining projects, the permitting process involves preparation of an environmental impact report, development of mining and reclamation plans, attainment of zoning variances, and attendance at public hearings. An excellent summary of issues related to mining activity in California is presented in Tooker and others (1990).

### Land Use Planning

Most of the difficulties in securing mining permits stem from the intense competition for land use in California. In fact, land-use conflicts are the most common issues debated at local government public hearings. As a result, land use planning, which is an effort to attain the most beneficial use of land in any given area, has become one of the most important functions of local government agencies.

Most assessments of land for planning purposes can be based on readily observable surface characteristics. Wetlands can be evaluated for grazing potential, timberlands can be appraised for lumber, and soils can be classified for agricultural purposes. However, it is difficult to similarly assess the mineral potential of a particular area with a high degree of certainty. Consequently, in past years mineral potential of land has often not been seriously considered in the land use planning process because of the general lack of readily available scientific information.

## The Surface Mining and Reclamation Act

In 1975, California legislators took measures to increase the mineral resource base-line information available to land use planners by enacting the Surface Mining and Reclamation Act of 1975 (SMARA). The act provides for reclamation of mined lands and directs the State Geologist to classify land within California according to the presence or likely occurrence of significant mineral deposits. The mineral land classification reports and maps are transmitted by the State Mining and Geology Board (SMGB) to appropriate lead agencies who are required to incorporate the information in their general land-use plans.

It is important to note that land recognized by the State Geologist as mineral-bearing is not necessarily reserved for mining. Rather, it is a means to provide unbiased, scientific information about mineral resource occurrence to local governments who retain the authority to control the use of land within their jurisdictions. The effort ensures that information about mineral potential of land is recognized and considered before land use decisions are made that could preclude future mining.

### The California Mineral Land Classification System

#### Mineral Resource Zones

Mineral land classification involves dividing land into various Mineral Resource Zones (MRZ) that reflect varying degrees of mineral potential. The MRZ nomenclature and criteria adopted by the SMGB (1983) are shown in Figure 1 on what is referred to as the California Mineral Land Classification Diagram (definitions of terms in the diagram are presented in the inserted Glossary). The California Mineral Land Classification Diagram is a modification of a mineral resource classification scheme developed by the U.S. Bureau of Mines (USBM) and the U.S. Geological Survey (USGS) (1980) that presents a relationship between mineral resource occurrence and economic significance. The horizontal axis of the diagram represents the degree of knowledge about mineral occurrence, while the vertical axis portrays economic characteristics of mineral deposits (ore grade and size of deposit). The diagram has been divided into four parts for the purpose of presenting basic information regarding mineral resource potential of land:

- Areas of No Mineral Resource Significance
- Areas of Identified Mineral Resource Significance
- Areas of Undetermined Mineral Resource Significance
- Areas of Unknown Mineral Resource Significance

As shown in Figure 1, each of the above divisions relates directly to and incorporates one of the four basic Mineral Resource Zone (MRZ) categories established through law or SMGB policy. The specific definitions of each MRZ category are given below. Note in both Figure 1 and in the MRZ definitions that categories MRZ-2 and MRZ-3 each have two subcategories. MRZ-2 is divided mainly on the basis of degree of knowledge regarding economic significance of known mineral deposits while MRZ-3 is divided mainly on the basis of degree of knowledge regarding the presence of mineral deposits of potential economic significance. Following are MRZ definitions:

- MRZ-1:** Areas where available geologic information indicates there is little likelihood for the presence of significant mineral resources.
- MRZ-2a:** Areas underlain by mineral deposits where geologic data indicate that significant measured or indicated resources are present. Areas classified MRZ-2a contain discovered mineral deposits that are either measured or indicated reserves as determined by such evidence as drilling records, sample analysis, surface exposure, and mine information.
- MRZ-2b:** Areas underlain by mineral deposits where geologic information indicates that significant inferred resources are present. Areas classified MRZ-2b contain discovered mineral deposits that are either inferred reserves as determined by limited sample analysis, exposure, and past mining history or deposits that presently are sub-economic.
- MRZ-3a:** Areas containing known mineral occurrences of

- undetermined mineral resource significance.
- MRZ-3b:** Areas containing inferred mineral occurrences of undetermined mineral resource significance. Land classified MRZ-3b represents areas in geologic settings that appear to be favorable environments for the occurrence of specific types of mineral deposits.
- MRZ-4:** Areas of no known mineral occurrences where geologic information does not rule out either the presence or absence of significant mineral resources.

The distinction between the MRZ-1 and MRZ-4 categories is important for land-use considerations. It must be emphasized that MRZ-4 classification does not imply that there is little likelihood for the presence of mineral resources, but rather there is a lack of knowledge regarding mineral occurrence.

Classification Criteria

To be considered significant for the purpose of mineral land classification, a mineral deposit, or a group of mineral deposits that can be mined as a unit, must meet marketability and threshold value criteria adopted by SMGB (1983). The criteria vary for different mineral categories depending on (1) whether they are strategic or nonstrategic minerals, (2) their uniqueness or rarity, and (3) their commodity-type category (metallic minerals, industrial minerals, or construction minerals). For example, to be considered significant, the threshold value of the marketable product for a metallic ore deposit is 500,000 1978 dollars, 1,000,000 1978 dollars for an industrial mineral deposit, and 5,000,000 1978 dollars for a construction aggregate deposit (multiply 1978 dollars by 2 to calculate threshold value in October 1993 dollars).

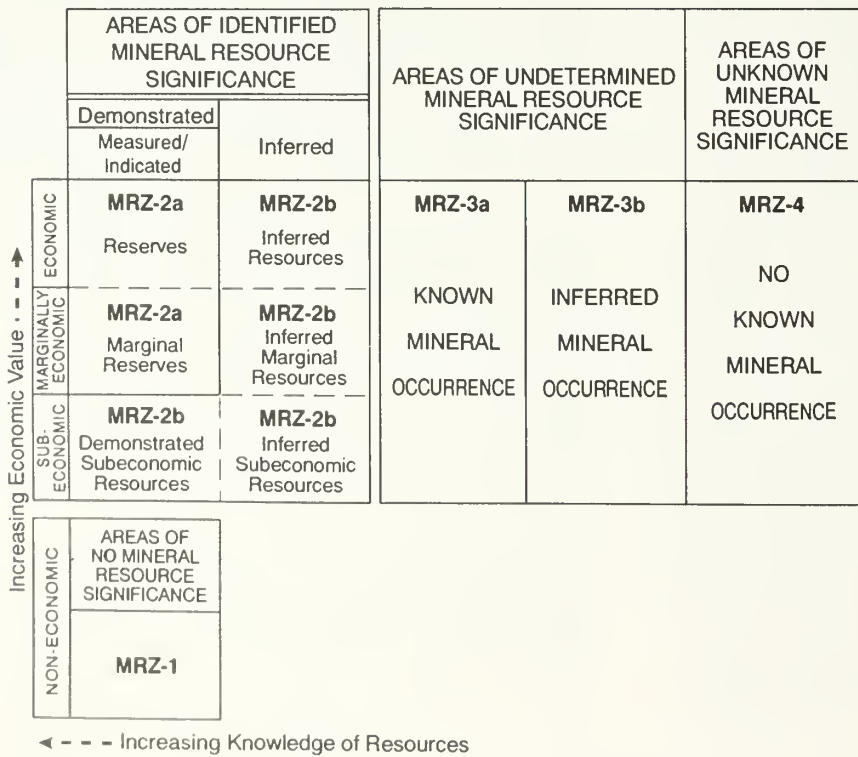


Figure 1. California Mineral Land Classification Diagram





Figure 2. Map of California showing priority areas for mineral land classification.

## Mineral Deposits

Consideration for mineral land classification is given to all non-fuel minerals of potential economic importance in determining what classes of metallic and nonmetallic mineral deposits are likely to occur within the project area. There are ten genetic classes that are recognized in mineral land classification studies. These are:

- deposits formed by hydrothermal processes.
- deposits formed by contact metasomatism.
- deposits formed by magmatic segregation.
- deposits formed by sedimentation.
- deposits formed by metamorphism.
- deposits formed by evaporation.
- deposits formed by residual concentration.
- deposits formed by mechanical concentration.
- deposits formed by bacteriological processes.
- industrial mineral deposits formed by diverse processes.

Only those classes for which direct or indirect evidence indicates the presence or likely occurrence of significant deposits are addressed in the classification report covering the project area.

## Scope of Studies

Unlike earlier studies conducted by the Division of Mines and Geology (DMG) that emphasized the reporting of mining activity within California, mineral land classification studies address the overall mineral potential of land through the identification of local and regional geologic factors that control or influence the formation of mineral deposits. Although mines and prospects are viewed as important sample points for accumulating geologic data on the nature and distribution of deposits within a mineralized area, information such as the extent of workings, years of activity, total production, and current status, is not normally presented.

Mineral land classification studies involve researching geologic and mining-related literature, compiling geologic maps, and plotting reported mines and prospects using publications and mine data of the DMG, USGS, USBM, and U.S. Bureau of Land Management (BLM). The projects involve site investigations of many of the known mines and mineral prospects in the project area, limited sampling of rocks for chemical analyses, geophysical surveys, and some geologic mapping. The research, field, and analytical data are integrated and evaluated to classify land into the four MRZ categories described above.

## Priority Areas

California's Mineral Land Classification studies have principally focused on three areas of California: (1) metropolitan regions, (2) the Sierra Nevada foothill region, and (3) the California Desert Conservation Area (CDCA) (Figure 2). As originally mandated by SMARA, the initial mineral land classification studies were confined to metropolitan areas where aggregate resources were being lost to urban development at an alarming rate.



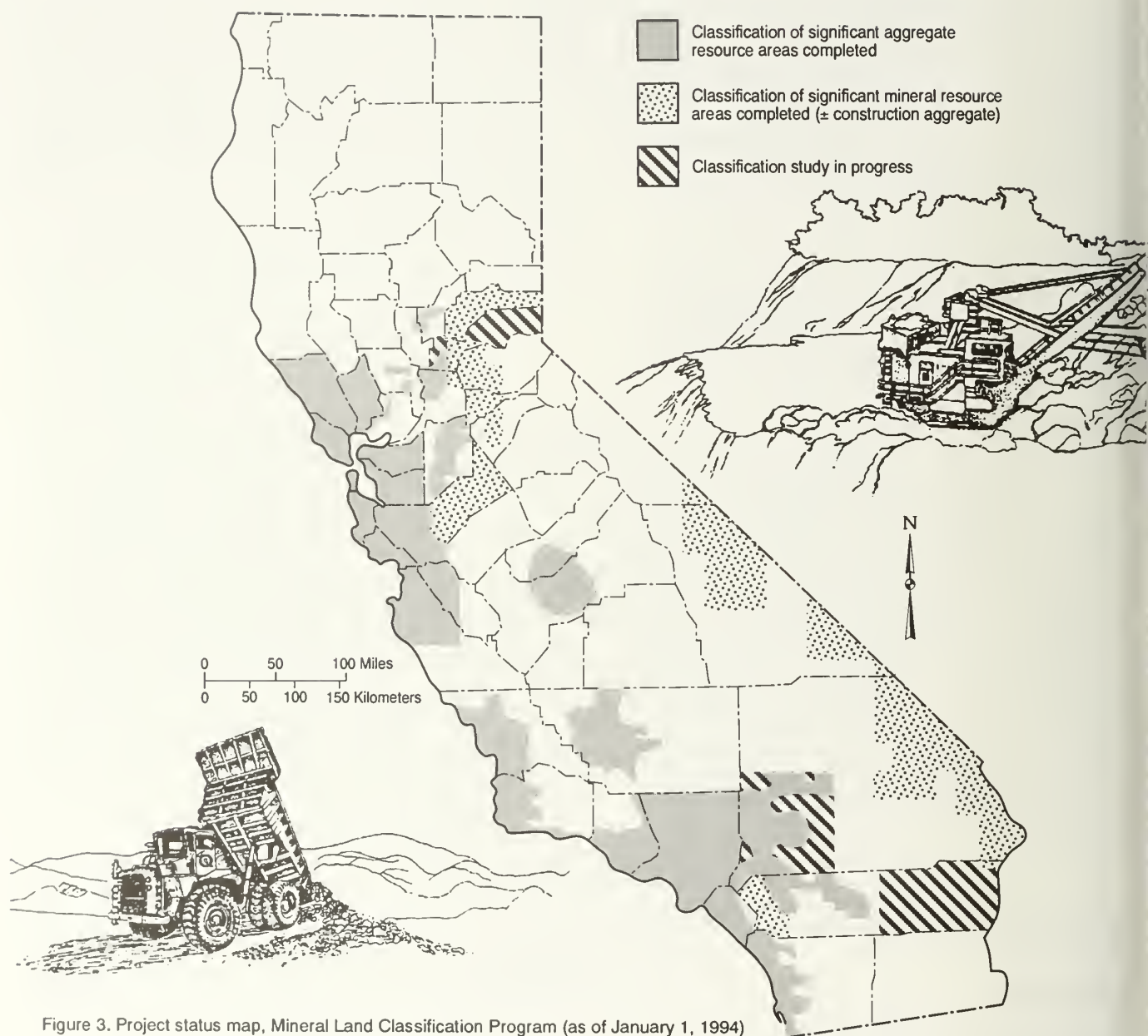


Figure 3. Project status map, Mineral Land Classification Program (as of January 1, 1994)

Revision of SMARA in 1980 authorized mineral land classification studies in non-urban areas. The Sierra Nevada was selected as a priority region because of its remarkable mineral resource wealth and because of dramatic population growth. The Mojave Desert Basin and Range region also was selected as a priority area because of pending withdrawals of large tracts of desert lands from mineral entry (national park and monument expansion, military reserve boundary modification, and proposed wilderness areas). Figure 3 shows areas for which DMG has completed mineral land classification studies. At present, approximately 23 percent (35,700 square

miles or 92,400 km<sup>2</sup>) of California has been classified. Classification of 7,000 square miles (18,000 km<sup>2</sup>)

In accordance with policy adopted by the SMGB (1983), DMG also conducts mineral land classification studies of land parcels owned or controlled by individuals or companies who are interested in preserving the property for mineral development. In these cases, an interested party "petitions" the SMGB for a mineral land classification study to be performed. If the petition is accepted, the SMGB directs the State Geologist to classify the property, and the subsequent report is transmitted to the appropriate lead agency.

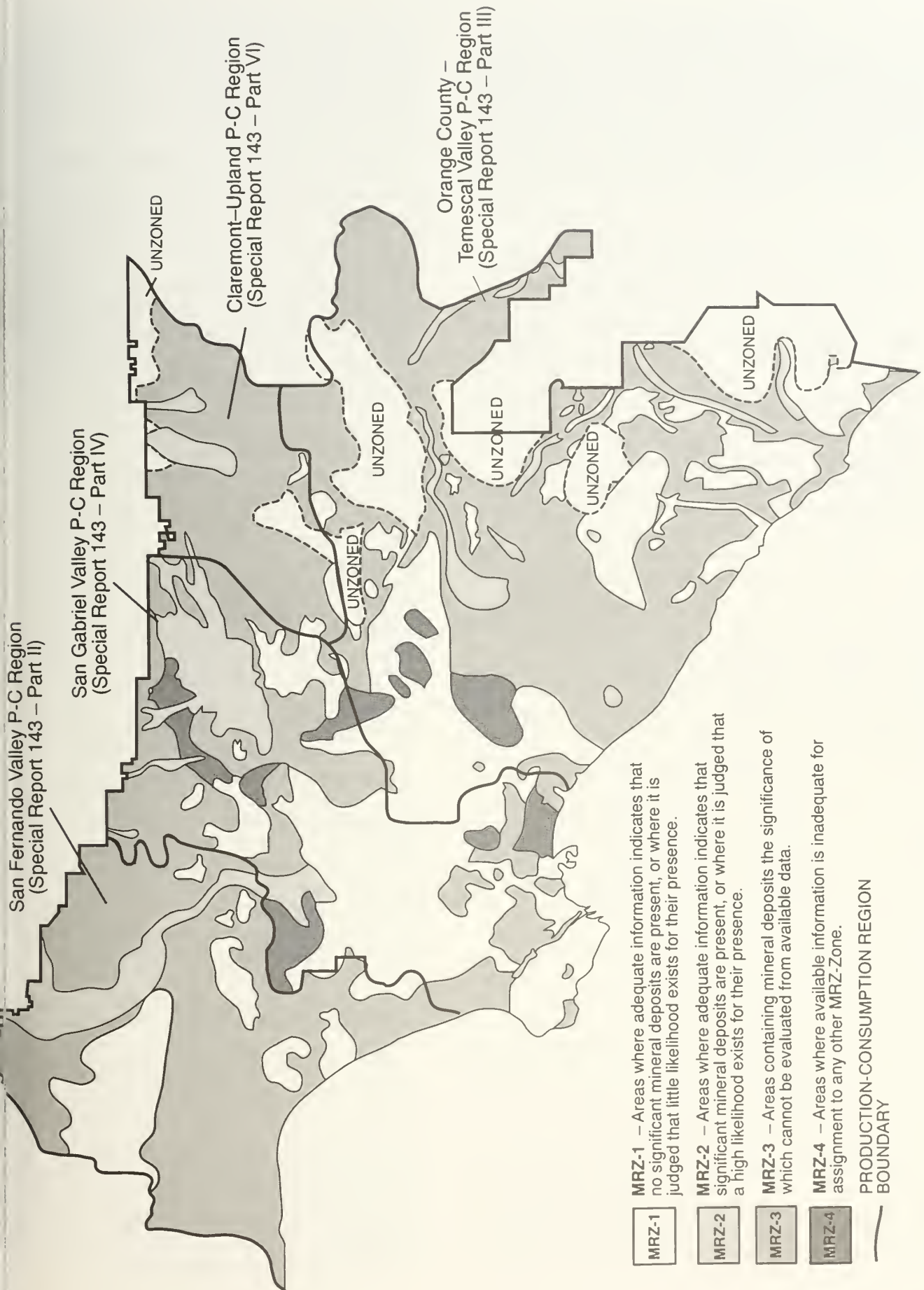


Figure 4. Generalized aggregate resource mineral land classification, Los Angeles metropolitan area.



## Metropolitan Areas

The first area classified under SMARA was the greater Los Angeles metropolitan region, with classification initiated in October 1978. Here, local sand and gravel resources that would have been adequate to meet the construction needs of the metropolitan area for many centuries had been reduced to a few decades' supply due to urban development on or adjacent to major alluvial sand and gravel deposits.

The central part of the Los Angeles metropolitan area historically has obtained most of its construction aggregate supply from four major aggregate producing districts. Several other production districts are in adjacent urbanizing areas, such as San Bernardino, Saugus-Newhall, Palmdale, and Ventura County (Evans and others, 1979). Since the cost of processing alluvial sand and gravel deposits in the Los Angeles area does not vary greatly from one district to another, the extent of the market region served by a particular production district is generally determined by the relative transportation costs in delivering aggregate from the production district to the point of use.

In California, minimum haulage rates for aggregate are regulated by the State Public Utilities Commission (PUC). PUC publishes maps and tables listing relative aggregate haulage rates from selected points to all parts of the metropolitan area. PUC's haulage rate maps and lists proved useful in determining individual market areas for the major production districts in the Los Angeles metropolitan area. These production districts, and the market areas they serve, came to be known as aggregate production-consumption (P-C) regions. Each P-C region was then evaluated and classified separately (Figure 4).

Following classification, population growth trends and per capita consumption of aggregate were evaluated to resource areas containing potentially minable aggregate deposits were identified and volumetric calculations of aggregate resources made to compare resources with projected 50-year needs.

Between 1978 and 1985, DMG classified about 8,000 square miles (20,700 km<sup>2</sup>) of land in southern California including parts of Los Angeles, Ventura, Orange, Riverside, San Bernardino, and San Diego counties. Over 46 billion tons of aggregate resources were identified in southern California, of which only 2.28 billion tons were permitted for mining. Additional mineral land classification studies in southern California have been completed in San Luis Obispo and Santa Barbara counties.

In northern California, similar mineral land classification studies were completed for the metropolitan areas of San Francisco Bay, Monterey Bay, Marin and Sonoma counties, Sacramento-Fairfield, Yuba City, Stockton-Lodi, Fresno, and Bakersfield (Figure 3). Currently, a classifica-

tion study that addresses aggregate and other mineral resources is being performed in Stanislaus County. An overview of DMG's mineral land classification studies of aggregate resources in metropolitan areas of California is presented in Beeby (1988).

## Sierra Nevada Foothills Region

The State Geologist initiated mineral land classification studies in the Sierra Nevada foothill region in 1978. To date, about 3,000 square miles (7,800 km<sup>2</sup>) of land in the Sierra Nevada foothills have been classified. In 1985, another study of 1,000 square miles (2,600 km<sup>2</sup>) is in progress. As illustrated in Figure 3, parts of the region were completed on a 15-minute-quadrangle basis, whereas in one study, Nevada County, was completed on a whole-county basis. An additional whole-county mineral land classification study of Placer County is in progress.

Most of the classification work in the Sierra Nevada region has been concentrated in the southern half of the metamorphic rock belt exposed along the western slope of the range between Lake Almanor on the north and Mariposa on the south (Figure 2). These rocks host the historic Mother Lode gold belt and many famous mining districts. Other minerals known to occur in the region include copper, zinc, lead, chromium, asbestos, manganese, tungsten, talc, barite, limestone, and dolomite. In addition, clay, silica sand, lignite, and placer gold deposits are hosted in Tertiary sedimentary deposits that overlay the metamorphic basement rocks.

Mineral potential of the Sierra Nevada metamorphic belt is high. Most of the mineral deposits that have been mined along the belt were discovered through simple surface observations by early prospectors. Therefore, it is likely that additional economic mineral deposits in the region will be discovered using modern exploration technologies. Unfortunately, mining permits are becoming increasingly more difficult to acquire in counties situated along the foothill region of the Sierra Nevada as land use competition intensifies with the ever growing population. However, information contained in mineral land classification reports can reduce the number of mineral deposits lost to incompatible land uses.

## California Desert Conservation Area

Much of the State Geologist's mineral land classification effort in the last 7 years has been focused in the California Desert Conservation Area (CDCA) (Figure 3) in anticipation of major congressional legislation that will adversely affect mineral production in the 39,000-square-mile (101,000-km<sup>2</sup>) region (25 percent of California's area). About 50 percent of the California's total mineral production is mined within the CDCA. Historically, at least 50 different mineral commodities have been produced from the region.



The Federal Land Policy and Management Act of 1966 (FLPMA) required the Secretary of Interior, through the BLM, to inventory and identify all resource values of the CDCA (energy, minerals, grazing, recreational, environmental) and make recommendations to Congress regarding suitability of areas for wilderness designation. Areas designated wilderness by Congress will be withdrawn from mining and mineral exploration; about 9,400 square miles (24,000 km<sup>2</sup>) of land in the CDCA are already in national parks and monuments, and military reservations.

The BLM has identified about 3,300 square miles (8,500 km<sup>2</sup>) in the CDCA as suitable for wilderness designation (Bureau of Land Management, 1991). Legislation formerly carried by U.S. Senator Alan Cranston and currently by U.S. Senator Dianne Feinstein would increase the wilderness designation to more than 16,000 square miles (41,400 km<sup>2</sup>) (U.S. Bureau of Mines, 1992). The effect of such legislation would be to reduce the amount of land in the CDCA, administered by the BLM and now open to mineral exploration, by about 66 percent, most of which is covered by deep alluvium of the desert basin areas.

FLPMA mandated the USGS and the USBM to conduct geologic and mineral resource studies in the Wilderness Study Areas (WSA). At the direction of the SMGB, the Division of Mines and Geology initiated independent economic geologic studies in the CDCA in the early 1980s, emphasizing those areas subject to wilderness designation. To date, about 10,000 square miles (25,900 km<sup>2</sup>) of land have been classified in the CDCA with 6,000 square miles (15,500 km<sup>2</sup>) in progress (Figure 3).

## PROJECT ACCOMPLISHMENTS

During the 15 years that the DMG has been implementing its Mineral Land Classification Project, 35,700 square miles (92,400 km<sup>2</sup>) of California have been classified for mineral resource potential (Figure 3). During this time, a significant number of cases have been documented where the success of companies obtaining permits to mine have been attributed largely to information provided in mineral land classification reports. The following cases illustrate how mineral land classification studies benefit local governments, the mining industry, and the public in making responsible land use decisions and conserving our diminishing natural resources.

### Hospital Creek Fan in San Joaquin and Stanislaus Counties

In 1988 DMG classified a 1.7-square-mile (4.4 km<sup>2</sup>) area of the Hospital Creek alluvial fan in southern San Joaquin County and northwestern Stanislaus County as a potential source of aggregate suitable for portland cement concrete (PCC) (Jensen and Silva, 1988). The deposit is in an urbanizing region where PCC-grade

aggregate is scarce. Since the classification report was published, three aggregate companies have acquired land in the area classified. One company was recently granted a permit to mine sand and gravel and a second is applying for a mining permit. The mineral potential and market significance of this deposit was not recognized until reported by Jensen and Silva (1988).

### San Joaquin River in Fresno County

The mineral land classification study of the Fresno area (Wiedenheft-Cole and Fuller, 1986) informed local planners and the public of the importance of aggregate resources in the San Joaquin River. These deposits are the only local source of sand and gravel serving this rapidly growing area. At the time of the report, real estate developers were proposing home development expansion along the bluffs overlooking the San Joaquin River. There was also strong support to establish a parkway along the river. Learning from the report that mining was an interim land use, parkway advocates then supported continued aggregate extraction along the river. The lead agencies involved decided against further home development and permitted continued in-stream mining with reclamation of the land as parkway.

### Santa Clara River in Western Ventura County

Mineral land classification of western Ventura County (Anderson and others, 1981) gave local planners objective mineral resource data on which to base critical land-use decisions. This allowed them to define long-term goals for in-stream mining and the management and protection of the Santa Clara River, which had badly eroded farmlands, riparian habitat, and bridge abutments during the past decade. A regional plan has been implemented to conserve and protect mineral and other important natural resources along the river. At the same time, the SMARA classification data identified alternative sources of aggregate in less sensitive areas, so a local source of low cost aggregate is still available. The SMARA classification work focused attention on resource issues in the area, provided unbiased resource and market data on construction aggregate, and allowed local government to resolve permitting process issues that were years in the making.

### Apperson Ridge in Alameda County

More than one billion tons of high-quality concrete-grade aggregate were identified on Apperson Ridge in Alameda County during the South San Francisco Bay Area SMARA classification project (Stinson and others, 1987a). Attempts to obtain a mining permit for this property had been unsuccessful for the past 30 years. DMG's study showed the region was being rapidly depleted in its local supply of aggregate and unless new properties were permitted, aggregate reserves would be

exhausted in fewer than 20 years. The study also identified many unpermitted, but promising, aggregate deposits. With this regional perspective of both need and resource availability, local planners worked with the permit applicant on Apperson Ridge and a mutually acceptable mining and reclamation plan was developed and accepted. This large new permitted deposit greatly increased the reserve base and increased the options of local planners in protecting sensitive environments while at the same time maintaining a source of vital low-cost aggregate to maintain the urban infrastructure of their jurisdictions.

### Castle Mountain Gold Deposit in the Mojave Desert

Prior to exploration and development of the Castle Mountain Mine in the late 1980s, DMG geologists classified the area as containing significant inferred resources of gold (Joseph, 1985). They characterized the property as having distinct geologic settings within which undiscovered precious metal deposits may reasonably be expected to exist. Today, the mine ranks as a "world-class" deposit whose reserves exceed 2 million troy ounces of gold. Annual production of the mine is over 100,000 troy ounces of gold, valued at more than 35 million dollars.

### Land-use conflict in Los Angeles County

A proposal to permit the development of a subdivision that would overlook an existing aggregate mining operation in Soledad Canyon was submitted to the County Regional Planning Commission. As proposed, the development would have resulted in the curtailment of the mining operation and the effective loss of mineral resources. Information presented in DMG's Saugus-Newhall-Palmdale mineral land classification study (Joseph and others, 1987) provided vital aggregate resource data to the Planning Commission. Using this information, the commission modified the development proposal so that mining continued without loss of resource.

## CONCLUSION

The main value of DMG's mineral land classification maps is to help prevent unnecessary loss of valuable mineral deposits by requiring local governments to consider available mineral information when making land-use decisions and encouraging them to make firm plans to protect areas that contain significant mineral deposits. In addition, California's efforts will target favorable areas for mineral exploration and development, which should lead to an expanded industrial base, greater employment opportunities, and enhanced economic growth.

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## GLOSSARY

### California Mineral Land Classification Diagram Nomenclature

The following definitions explain the nomenclature associated with the California Mineral Land Classification Diagram. These definitions have been adapted from U.S. Bureau of Mines and U.S. Geological Survey (1980) and Bates and Jackson (1987). It is important to refer to these definitions when applying the different resource categories shown on the diagram. Particular attention should be given to the distinction between a mineral deposit and a resource and to how mineral deposits may relate to resources.

**MINERAL DEPOSIT:** A mass of naturally occurring mineral material, (e.g., metal ores or nonmetallic minerals, usually of economic value, without regard to mode of origin). The mineral material may be of value for its chemical and/or physical characteristics.

**MINERAL OCCURRENCE:** Any ore or economic mineral in any concentration found in bedrock or as float; especially a valuable mineral in sufficient concentration to suggest further exploration.

**ECONOMIC:** Implies that profitable extraction or production under defined investment assumptions has been established, analytically demonstrated, or assumed with reasonable certainty.

**MINERAL RESOURCE:** A concentration of naturally occurring solid, liquid, or gaseous material in or on the earth's crust in such form and amount that economic extraction of a commodity from the concentration is currently or potentially feasible. The terms reserves and mineral resource are synonymous in this report.

**RESERVES:** That part of the resource base that could be economically extracted or produced at the time of determination. The term reserves need not signify that extraction facilities are in place and operative. In the case of aggregates, the term includes only permitted resources.

**IDENTIFIED MINERAL RESOURCES:** Resources whose location, grade, quality, and quantity are known or estimated from specific geologic evidence. Identified mineral resources include economic, marginally economic, and sub-economic components. To reflect varying degrees of geologic certainty, these economic divisions can be subdivided into demonstrated and inferred.

**DEMONSTRATED:** A term for the sum of measured plus indicated.

**MEASURED:** Quantity is computed from dimensions revealed in outcrops, trenches, workings, or drill holes; grade and/or quality are computed from the results of detailed sampling. The sites for inspection, sampling, and measurement are spaced so closely and the geologic character is so well defined that size, shape, depth, and mineral content of the resource are well established.

**INDICATED:** Quantity and grade and/or quality are computed from information similar to that used for measured resources, but the sites for inspection, sampling, and measurement are farther apart or otherwise less adequately spaced. The degree of assurance, although lower than that of measured resources, is high enough to assume continuity between points of observation.

**INFERRED:** Estimates are based on an assumed continuity beyond measured and/or indicated resources, for which there is geologic evidence. Inferred resources may or may not be supported by samples or measurements.

**MARGINAL RESERVES:** The part of the demonstrated reserve base that, at the time of determination, borders on being economically producible. Its essential characteristic is economic uncertainty. Included are resources that would be producible, given postulated changes in economic or technologic factors.

**MARGINAL RESOURCES:** The part of the inferred resource base that, at the time of determination, would be economically producible, given postulated changes in economic or technologic factors.

**SUB-ECONOMIC RESOURCES:** The part of identified resources that does not meet the economic criteria of marginal reserves and marginal resources.







# California Mineral Education Foundation Conference Model: Changing Public Perception of the Mineral Industries

by  
Greg R. Wheeler<sup>1</sup>

## ABSTRACT

Few members of the general public have a clear understanding of mineral resources. Most people do not know how minerals are mined or why they must be extracted from many diverse locations. Many people acquire knowledge of mineral development from mass media sources with incomplete details or obvious anti-mining bias. The California Mineral Education Foundation was formed in 1991 to provide educational opportunities for the public and industry.

There have been major changes in earth science teaching requirements for kindergarten through 12th grade (K-12) curricula since the passage of California Senate Bill 813 in 1983. Model graduation standards, curriculum standards and the state science framework mandate substantial coverage of geoscience topics. The California State Commission on Teacher Credentialing has completed changes in multiple subject and single subject science credentials which will require more geoscience preparation for all teachers. The need for pre-service and in-service education in geoscience is at an all time high. Teachers must have continuing education to maintain their credentials and many are now seeking information in geoscience.

The California Mineral Education Foundation designed and conducted the California Mineral Education Conferences held in August 1991 and 1992. The conferences involved lectures and field trips on mining geology, environmental problems and political concerns. Master teachers were employed to share how they get across mineral resource concepts in the classroom. Ninety-six percent of the participants stated that they had changed to a more positive perception of mining after taking the three day course.

## INTRODUCTION

Farmers have long complained that people who live in urban areas don't know where food comes from or how it is brought to market. This point was graphically illustrated to me when a young neighbor was astonished to discover that peas grow in pods on vines in my backyard. People know even less about the minerals industry. Very few people are aware that the extraction of minerals from the Earth is essential to all but the most primitive humans. The progress of man has been related to minerals. This fact is acknowledged in phrases like Stone Age, Bronze Age and Iron Age. Today's civilization seems totally unaware that roads, walls, glass, metal and all other products not grown, ultimately trace their origin to mining. There is obviously a tremendous need for the mining community to educate the public. This education benefits everyone.

## PUBLIC PERCEPTION

The lack of knowledge linking familiar and important necessities of modern life to mining is a major reason mining is held in low esteem. After all, if no one uses the materials hauled from the Earth, why is mining making all those ugly holes? Mass media is often partly to blame for this public knowledge deficiency. Rather than write complex, in depth articles that fully explore the reasons for mining and modern methods of extraction, it is far easier to titillate with tales of mass destruction from mine wastes. The vast expanse of a large open pit clawing a virgin forest or providing dust and noise in suburbia are photographically dramatic and journalistically attractive topics. Many journalists have no background at all in economics, environment or mineral resources but feel competent to write exposés on local mining operations. The public reads these presentations and files the infor-

mation for use at the next city planning meeting. Recently, numerous city councils like those in Los Angeles, Sacramento and San Francisco voted to support the Desert Wilderness Act which would authorize closure of two-thirds of the exposed bedrock in southeastern California desert to mining. The counties where the desert is located strongly oppose the wilderness designation.

The mining community has only recently awakened to its responsibility to educate itself and others on the whole picture of resource development. Miners tend to be people who are not good at public relations. Miners favor hard work in isolated, harsh environments and tend to feel the importance of their labor should be self evident. When forced to defend their right to extract mineral resources most mining companies react defensively or even defiantly. They are incredulous that anyone should question their operation. They think people know how critically important our products are. They think the voters know the importance we put on environmental monitoring and habitat rehabilitation. But the public does not know. We must tell them.

Most confrontations over mining permits, wilderness areas, and environmental regulations are handled only in the short term. To be sure, some of the battles stretch over many years, but rarely is a well grounded education on the issues part of the discussion. Each side tends to feel its position is so clear it requires no discussion. Groups in this position can never resolve their differences, they can only try to block the efforts of the opposite group. Lobbyists are hired, half truths are spread and decisions are made.

## EARTH SCIENCE CURRICULUM CHANGES IN CALIFORNIA

Earth science education changes evident in California today trace their roots to the passage of Senate Bill 813 (passed in 1983). It requires two years of science, including both life and physical science, in secondary schools. The legislation does not require a separate year in each area of science, but most districts elected to create separate, one-year courses for life and physical sciences.

Model Graduation Standards published in 1983 proposed inclusion of earth and space science concepts within physical science courses. This theme was continued in Model Curriculum Standards for grades 9 through 12 published in 1985. The graduation standards developed by the State Board of Education required students to study earth and space science topics such as plate tectonics, geologic resources, geologic hazards, remote sensing, and paleontology.

The California Assessment Program (CAP) developed exams to test the "fitness" of school educational programs. The eighth grade CAP tests began in 1985 and

gave parity in coverage to earth, physical, and life sciences. These tests served to emphasize changes in educational expectations, and resulted in considerably more earth science in grades seven and eight than was previously the case. For state budget and political reasons, the CAP tests for grades six, ten, and twelve were not widely used before the program ended in 1990. The State Department of Education is now piloting new tests for grades five, eight and ten. These new CAP tests continue to emphasize equal treatment for earth, physical and sciences.

The strong trend toward inclusion of earth science in K-12 curriculum is again obvious in the publication of the *Science Framework for California Public Schools Kindergarten Through Grade Twelve* approved by the State Board of Education in 1990. The Science Framework divides science into physical, life, and earth science categories. The earth science chapter includes discussion of astronomy, geology and natural resources, oceanography, and meteorology. It is obvious that in graduation standards, model curricula, science frameworks and tests, the State Board of Education has realized and published the importance of earth science education.

## THE ROLE OF CALIFORNIA UNIVERSITIES

The state's post-secondary schools have been slow to recognize the major changes required of science education in our public schools. In July 1986, the combined Academic Senates of the California Community Colleges, the California State University, and the University of California released a report outlining science requirements for incoming freshman. The report stated that college bound high school students should take physics, chemistry, and biology. The only mention of earth sciences was in the questions and answers section where it was suggested that earth science should be taught in junior high as preparation for the "fundamental sciences." This document, *Statement on Preparation in Natural Science Expected of Entering Freshman* (California State Department of Education, 1986), sent a contradictory message on earth science education in secondary schools. Caught between state frameworks with guidelines that required earth science and universities that would not accept these classes as science courses needed for entrance, most school districts offered earth science only in junior high or to non-college bound high school students.

The quagmire created by conflicting standards is beginning to dissipate. In 1994, entering freshman at the University of California will be required to take two years of laboratory science and three years are recommended. Among the "A-F" requirements published in the University of California Preparing for Admissions document



1991), the "D" requirement reads "... laboratory courses in earth/space sciences are acceptable if they have as prerequisites or provide basic knowledge in biology, chemistry, or physics." The California State University policy of accepting University of California approved courses for admissions means that, by 1994, earth science courses will be accepted at all California public universities. The wording in the document is still flawed. The Far Western Section of the National Association of Geology Teachers (FWS-NAGT) tried hard to persuade the University of California Board of Admissions and Relations to Schools (BOARS), which prepared the document, to treat earth science as an equal to other sciences. FWS-NAGT pointed out the strong endorsement of earth science in the State Board of Education requirements. FWS-NAGT cited states like Montana and North Carolina that require earth science options for college entrance. The BOARS committee, which has never included an earth scientist, refused all requests to offer testimony on behalf of earth science inclusion. Nevertheless, the new admissions document does open a door too long closed. Well-designed geology classes or other earth science classes will now be college acceptable.

The importance of earth science education has been nationally recognized. A policy statement on the critical nature of earth science education was endorsed in 1987 and 1988 by earth science organizations and by the National Science Teachers Association (NSTA) and the Council for Elementary Science International (CESI) (Far Western Section of NAGT newsletter 1988). The Council of Scientific Society Presidents (CSSP) passed a resolution regarding the teaching of geoscience at the pre-college level in 1991. The resolution resolved "that substantial study of geoscience (e.g., astronomy, geology, soil science, oceanography, and meteorology) be made part of the pre-college curriculum in the United States' middle and high schools, and that its status as a laboratory science be acceptable for college admission along with biology, chemistry, and physics." It further states "geoscience shall be one of the themes for the teaching of science in the elementary schools of our country." There is a national consensus of science educators and scientists in general, that geoscience, the most modern term for earth science, should be a strong part of all science education. This national direction will continue to pressure California universities to regard geoscience equally with physics, chemistry, and biology.

## TEACHER PREPARATION

The preparation and credentialing of California teachers in geosciences has been difficult. The 1970 Ryan Act established single subject credentials for teachers at secondary schools. Only life science and physical science credentials are options for science teachers. Under cur-

rent requirements, physical science teachers must be prepared to teach physics, chemistry or any of the earth sciences. This means that although earth science is treated equally with physics and chemistry by the State Department of Education guidelines, and is progressively better treated in university entrance requirements, teachers must still be prepared as physical science teachers with earth science merely a subset of their broader studies. This has resulted in universities constructing long lists of course requirements. These course requirements, called waiver programs because they have waived the National Teachers Exam (NTE) required for entrance to credential programs, usually take more than four years to complete and have few students. Only a few schools like CSU Sacramento, CSU Bakersfield, San Francisco State University (SFSU), and San Jose State University (SJSU) offer earth science options for physical science waiver programs. The result of these rigorous requirements and the historic lack of earth science interest in K-12 science programs is that few science teachers are prepared to teach these subjects.

There are several possible solutions to the credentialing dilemma. The California Commission on Teacher Credentialing (CTC) has been revising waiver program standards for life and physical science credentials. Revisions for both waiver program standards now contain language requiring preparation to teach conceptual understanding about the planet earth, including natural resources and other earth materials, geomorphic and internal geologic processes, natural hazards and environmental issues, and the history of the earth and its life forms. Some modification must still be made to allow students to complete required classes in reasonable lengths of time. The CTC is also considering changes in the Ryan Act which would collapse the life and physical science credentials into one science credential with separate additional courses for students completing the waiver program in biology, chemistry, geosciences, or physics. This would abolish the former physical science waiver program requirement of preparation in chemistry, earth sciences, and physics. This seems long overdue. An earth science credential could enable more and better prepared teachers to address earth science areas within the state science framework.

Perhaps the method of qualification chosen by most incoming teacher credential candidates will be the new Content Area Performance Assessment (CAPA) exams. The CAPA tests replace the National Teachers Examination (NTE). CAPA tests include essay questions as well as multiple choice questions. CAPAs for life science and physical science credentials correspond to the new content standards governing waiver programs with the exception that the geoscience content is heavily weighted towards geology. Whether through a waiver program or

CAPA, earth science teachers need to demonstrate great breadth. When final resolution is reached on the science credential structure, adjustments will need to be made in the CAPA exams.

Kindergarten through sixth and sometimes seventh and eighth grade instructors generally possess multiple subject credentials. Both the multiple subject waiver and exam have been recently revised to include earth and space science. The waiver guidelines for the multiple subject credential treats geoscience requirements equally with those in the life science and physical sciences. These 1990 requirements are being generally interpreted to require at least one course in geosciences (Slaymaker, 1991). The CAPA for the multiple subject credential is twenty percent science; one third of this multiple subject science content on the CAPA is geoscience with special emphasis on geology (Slaymaker, personal communication, 1992).

The significant increase in required geoscience content in K-12 classrooms requires substantial in-service opportunities to bolster the training of most teachers already holding credentials. The California State University (CSU) system has several important programs designed to provide both content and hands-on training in geoscience. Project Catalyst, at California State University, Fullerton, developed a comprehensive earth science teacher enhancement program for middle and high school teachers. The Bay Area Earth Science Institute (BAESI) at San Jose State University (SJSU) has developed educational partnerships among academic, business and government agencies. BAESI focuses on secondary school teachers. At California State University, Sacramento, the Schools and Colleges for the Advancement of Teaching Science (SCATS) brings secondary school science teachers to campus once a month for in-service training in all facets of science education. ESCATS at CSU Sacramento provides the same service for elementary school teachers.

The training and retraining of teachers to meet new California geoscience requirements provides a major opportunity for the mining community. Teachers holding K-12 teaching credentials must take 150 hours of continuing education course work every five years to maintain their credentials. Teachers will try to take these units in the disciplines most in demand and where they are most deficient.

## THE CALIFORNIA MINERAL EDUCATION CONFERENCE

The first California Mineral Education Conference held in August 1991, was organized by the California Mining Association and the Geology Department at California State University, Sacramento. Both the United States Geological Survey and the Division of Mines and

Geology contributed people and other resources; teachers attended. These teachers were mostly high school teachers but at least a few taught at each grade level from K-12. Forty percent said they had no formal training in earth science.

The second California Mineral Education Conference was held August 12-14, 1992. The California Mineral Education Foundation, a non-profit mining industry supported foundation, conducted the conference. The Geology Department at California State University, and California Department of Conservation's Division of Mines and Geology cosponsored the event; 95 K-12 teachers attended; 45% had no formal training in earth science.

The three day conferences begin with registration and a continental breakfast. Participants are given mining information materials supplied by companies, professional organizations such as the Society of Mining Engineers. Pre-registration materials give participants chance to select four of six classes taught the first day. Class choices in 1992 included: (1) History of mining and mining techniques, (2) Environmental concerns and reclamation, (3) Genesis of ore deposits, (4) Uses and value of minerals and where they are located, (5) Socio-economic issues and (6) Geo-Politics. Each class was 45 minutes long and was repeated four times during the conference. The classes are taught by professional mining engineers and geologists from the U.S. Bureau of Mines, the U.S. Geological Survey, the Division of Mines and Geology, and the Geology Department at California State University, Sacramento.

The second day of the conference was devoted entirely to classroom application of the first day's materials. Teachers were divided by grade level and each group was taught by a master teacher familiar with the class level and geologic information. The workshops were for 1-3, 4-6, 7-9 and 10-12 teachers. Each class learned how to best utilize mineral resource information at their grade level. The workshop teachers provided many hands-on and classroom ready exercises. Maps, rocks and minerals were supplied to every participant.

A barbecue was held the evening of the second conference. This setting allowed for casual conversation and gave mining representatives and classroom teachers time to pursue issues brought out during earlier presentations. A sluice and "salted" gravel provided a hands-on opportunity to gold pan.

The third day was field trip day. The first year conference went to the McLaughlin gold mine. At the McLaughlin Mine, Homestake Company geologists provided a tour of the mine and mill. Emphasis was placed on corporate concern for the environment and on reclamation. In 1992, the field trip was to Yuba Placer Gold



idge on the Yuba River and to the Teichert aggregate city. Both field trip stops provided teachers opportunity to discuss mining, economic and environmental issues. Participants could see mining and miners first hand. Many teachers expressed surprise that mining was going on in places they thought were urban.

The conferences were free to teachers but each conference cost about \$25,000 to conduct. Industry sponsors provided teacher stipends, donated materials and employees, and paid for box lunches and the barbecue. Many different individuals from companies, state agencies and federal agencies donated their time to make the conferences a success.

The results were very positive. At the 1991 conference, only 16% of participants began with a positive opinion of mining; 97% of the participants said they felt positive about mining at the end of the conference. In 1992, 91% of all participants left with a positive perception of mining. The 184 teachers with positive perceptions about mining will teach at least 110,000 students during their teaching careers. The impact of the conference will thus be magnified as committed, informed teachers spread information that conveys the whole mineral picture. The cost of providing this information to future voters is less than 36 cents per voter. These voters will make it far less necessary to pay lobbyists to argue the importance and needs of mining in acrimonious confrontations.

## CONCLUSIONS

Changes in the state of California science curriculum and teacher training make this an opportune time to provide teacher training in mineral resources. The training in workshops and seminars should include ample opportunity for the mining community to present a far more complete picture of the extractive industries than most teachers currently have. The California Mineral Education Conferences have been extremely successful in providing teachers with information and thus changing their perception of mining.

Mineral conferences are long-term commitments to the education of our children. The complete results will not be seen for a decade. In Robert Frost's poem *The Road Not Taken*, he describes how, when two roads diverged, he took "the road less traveled." The more worn road in mining has not solved our image problem. The public's lack of appreciation for the good done by the mining industry makes it increasingly difficult to provide the mineral resources that are so vital to us all. We must take the road less traveled. This road requires investment in the future and patience for results. It is the road of education. Mineral resource companies will not have a future unless they vigorously, honestly and skillfully pursue the education road. The California Mineral Education Foundation provides a road for mining companies, minerals clubs and others to fund education.

## ACKNOWLEDGMENTS

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# **Pumice for Stone-washed and Acid-washed Textiles: Benton Pumice Beds, Mono County, California**

by  
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## **ABSTRACT**

The Blind Springs Hill pumice beds are located 5 miles southwest of Benton, California in the foothills between the Benton Mountain Range and Blind Springs Valley. The best exposures of the pumice are in an area 0.75 miles west of Blind Springs Hill. The pumice is Quaternary ejecta material which came from the rhyolitic volcanoes in the Glass Mountain-Volcanic Tablelands area of Mono County. The pumice beds occur in two distinct layers separated by an unconformity. The upper layer is 0 to 11 feet thick and consists of coarse subangular pumice fragments, some of which are over 1.75 inches in diameter. The lower bed is medium to coarse grained with subangular fragments up to 1.0 inch. The lower bed is 0 to 9 feet thick. Overburden at the Blind Springs Hill deposit varies from 0 to 15 feet. There are approximately 1 million cubic yards of material in the deposit that can be mined.

The size distribution in the deposit is mostly fine with only 10.6% of the pumice fragments being over 0.5 inch in diameter, the minimum size needed for stone-wash or acid-wash applications. Suitability of pumice for the textile industry is quantified by standard 15-minute abrasion and absorption tests. In the Blind Springs Hill deposit, the plus 0.5 inch fraction has an abrasion loss of 33% which is too high for stone-wash application but it has an absorption capacity of 36% which makes it suitable for acid-wash applications in the textile industry. The abrasion and absorption properties of this deposit are within the range of those which have been measured for other pumice deposits within the United States.

## **INTRODUCTION**

Use of pumice in the textile industry has increased from a few hundred kilograms in 1970 to over 69,000 metric tons in 1992 (Bolen and others, 1993). This specialized application grew from 38,000 metric tons in 1991 and exceeded the 1992 tonnage used for abrasive and concrete admixtures and light weight aggregates.

Demand caused the price of pumice suitable for stone-wash and acid-wash textiles (mainly jeans) to rise to 13 cents per pound in El Paso and Los Angeles in 1992. That year, imports totaled 34% of the domestic pumice consumption. Major importers of laundry pumice were Ecuador, Mexico, and Turkey (Hoffer, 1994). In 1993-94 the price for laundry pumice was dropping.

These market conditions have led to a "Pumice Rush" in the American West, revitalizing old pumice mines once developed only for light weight aggregates or abrasive. One such deposit is the Benton Pumice Beds of Mono County, California (Figure 1).

## **GEOLOGY**

The Benton Pumice Beds lie in a block faulted trough between the White Mountains and the Sierra Nevada. Between these two regional structures is an uplifted block expressed topographically as the Benton Mountain Range. The Tertiary history of this region is dominated by the 570,000 year old Bishop Tuff which was deposited following the eruption of the Long Valley Caldera (Sorey and others, 1978; Krauskopf and Bateman, 1977). Tuff beds within the Tulare Formation of the western San Joaquin



Figure 1. Location of Benton Pumice beds, Blind Springs Valley, Mono County, California (T.2S, R.31E, Mount Diablo base & meridian, Glass Mountain 15-minute quadrangle).

Valley, 250 miles to the southwest have been suggested as correlative with the Bishop Tuff (Milliken, 1990). The rise of resurgent domes within the 6-mile-wide caldera and associated volcanism in the Inyo Craters and Mono Craters volcanic chains resulted in widespread pumice distributions in this area. The most recent pumice/obsidian eruption was about 10,000 years ago (Bateman, 1992).

## BENTON PUMICE BEDS

These pumice beds are located 5 miles southwest of Benton, California in the foothills between the Benton Mountain Range and Blind Springs Valley (Figure 2). The best exposures of the pumice are in an area 0.75 miles west of Blind Springs Hill. The pumice is Quaternary ejecta material which came from the rhyolitic volcanoes in the Glass Mountain-Volcanic Tablelands area of Mono County. The pumice beds occur in two distinct layers separated by an unconformity. The upper layer is 0 to 11 feet thick and consists of coarse subangular pumice fragments, some of which are over 1.75 inches in diameter. The lower bed is medium to coarse grained with subangular fragments up to 1.0 inch in size. The lower bed is 0 to 9 feet thick. Overburden at the Blind Springs Hill deposit varies from 0 to 15 feet. There are approximately 1 million cubic yards of material in the deposit that can be mined. The layers which has been mined for pumice are members of the Tuff of Taylor Canyon (Krauskopf and Bateman, 1977).

## PRODUCT SPECIFICATIONS

There are a number of criteria for identifying suitable pumice for treatment of textiles. The three most important are size, abrasion loss and absorption capacity (Hoffer, 1993).

Garment finishing with pumice consists of two distinct processes: acid washing and stone washing. Both processes require pumice fragments of at least 0.5 inch diameter. In acid-washing the pumice is impregnated with an oxidizing chemical such as potassium permanganate or bleach. The pumice is tumbled with the denim and the oxidizing chemicals released from the pumice bleach the garment. In this process, absorption capacity is the critical property of the pumice. In the stone-washing process, no chemicals are absorbed by the pumice; the abrasion of the rock against the garment produces the bleached look. In this application, low abrasion loss is the critical physical property for the pumice (Hoffer, 1994).

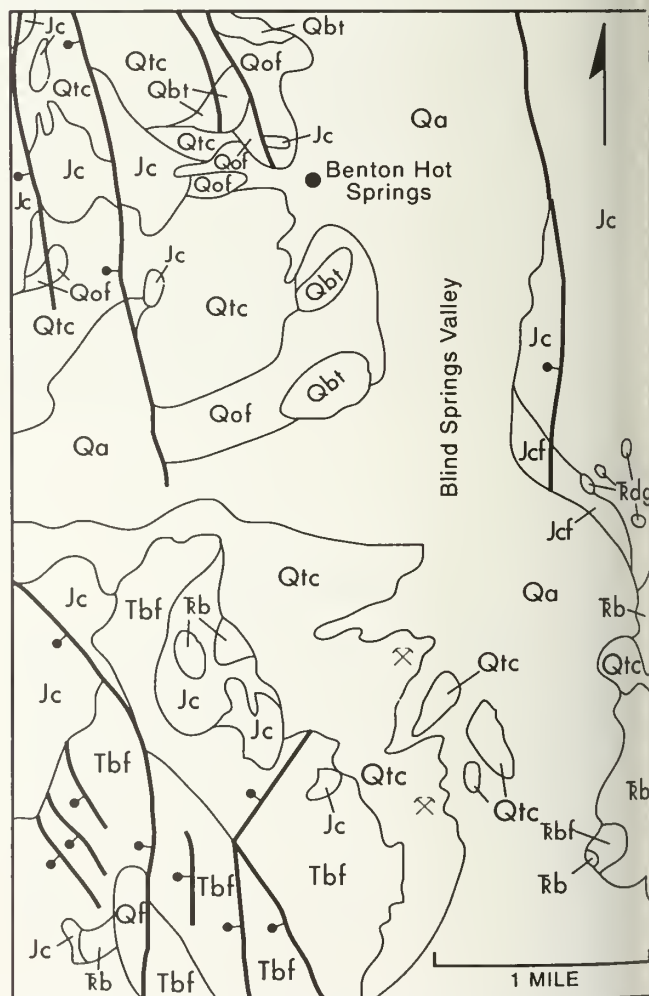


Figure 2. Geologic map of Blind Springs Valley. Adapted from Krauskopf and Bateman, 1977. Qa = alluvium, Qf = fanglomerate, Qof = older fanglomerate, Qbt = Bishop Tuff, Qtc = tuff of Taylor Canyon, Tb = basalt flows, Jc = granite of Casa Diablo Mountain, Jcf = fine grained granite of Casa Diablo Mountain, Tb = granodiorite of Benton Range, Tbf = fine grained granodiorite of Benton Range.



Table 1. Abrasion loss and absorption capacity for selected pumice deposits in the Western U.S. Data from J.M. Hoffer, personal communication, 1994.

PUMICE DEPOSIT	LOCATION	ABRASION LOSS (%)	ABSORPTION CAPACITY (%)
Tufflite	Coconino County, AZ	25.2	18.7
J.S. Pumice Co.	Mono County, CA	50.5	31.2
Glass Mountain Pumice	Siskiyou County, CA	37.0	13.8
Coso Junction	Inyo County, CA	26.3	23.1
Benton Pumice Beds	Mono County, CA	33.3	36.2
Hess Pumice Products	Oneida County, ID	38.9	10.8
Producers Pumice	Bonneville County, ID	42.0	23.3
Copar Pumice Co.	Sandoval County, NM	21.5	24.6
General Pumice Co.	Rio Arriba County, NM	26.3	22.0
Central Oregon Pumice Co.	Deschutes County, OR	26.0	24.4
Cascade Pumice Co.	Deschutes County, OR	37.0	38.0
Mineral Mountains	Beaver County, UT	23.0	10.1
Moody Pit	Coconino County, AZ	25.0	21.0
Little Glass Mountain	Siskiyou County, CA	30.6	28.7
Napa Valley	Sonoma County, CA	38.6	21.2
Obsidian Butte	Imperial County, CA	45.0	6.9
Puu Waawaa	Hawaii County, HI	28.0	35.0
Magic Reservoir	Blaine County, ID	27.6	32.2
Chiwawa Valley	Chelan County, WA	41.1	36.9

Size

Pumice fragments must be at least 0.5 inch in diameter. This requirement makes most Western pumice deposits unsuitable as a source for stone- or acid-wash textiles. The size distribution in the Benton deposit is mostly fine with only 10.6% meeting the 0.5 inch specification.

Abrasion and Absorption

Suitability of pumice for the textile industry is quantified by a standard 15-minute abrasion test and a five minute absorption test developed by the co-author of this article (Hoffer, 1991, 1992). In abrasion tests, samples are weighed and then tumbled for 15 minutes in a laundry (rifle) machine. After tumbling the fragments are reweighed; the loss of weight from tumbling is the abrasion loss. Abrasion losses of about 25% (by weight) are required for stone-wash applications. Abrasion loss measurements of foreign pumices show the following: Ecuador, 43%; Mexico, 25-31%; Turkey, 25%; Greece, 24% and Guatemala, 35%. Pumice deposits of the western U.S. have abrasion losses that range from 21% to 50% (Table 1).

By comparison, the Blind Springs Hill deposit's plus 0.5-inch fraction has an abrasion loss of 33% which is marginal for stone-washing.

In absorption tests, samples are weighed dry, submerged in water for 5 minutes and then reweighed. The increase in weight, due to absorption of water is expressed as a percentage and is termed the absorption capacity. An absorption capacity of at least 30% is preferred for acid washing pumice. Western U.S. pumice deposits have acid absorption capacities of 25% to 50% (Table 1)

The 0.5-inch fraction of the Benton Pumice Beds has a hydrochloric acid absorption capacity of 36% which makes it attractive for acid-wash applications.

The abrasion and absorption properties of the pumice from the Blind Springs Hill deposit are within the range of those which have been measured for other pumice deposits within the United States.

MINING METHODS

Previous mining activities near Blind Springs Hill have revealed a number of easily-accessible sites for pumice production without much overburden removal. In addition, there are large piles of pre-mined material that were never shipped. Front-end loaders take material to a classifier which separates the pumice into sizes shown in Table 2. Material over 3/8 inch are placed by hand into sacks.

ROYALTY

The size distribution in the two Benton Pumice Beds near Blind Springs Hill is shown in Table 2. Seven percent of pit run can be used for acid-wash textile treatment and

Table 2. Size and royalty distribution of Benton Pumice Beds

Size (inch)	Percent	Royalty* (pit run)
3/4 plus	6	\$4.06
5/8 to 3/4	1	0.68
3/8 to 5/8	16	0.64
1/8 to 3/8	30	1.20
pan	47	0.02 (occasional sales of sand)
Total	100	6.60

\* per U.S. short ton at mine site

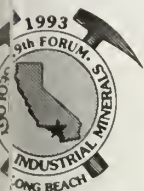
46% can be used for lightweight aggregate. The gross value of the pit run material is \$6.60 per U.S. short ton with 47% waste. Pumice that has been screened and loaded for shipping is sold under contract from the U.S. Bureau of Land Management for \$9.42 per U.S. short ton f.o.b.

## SUBSTITUTES

The rarity and high value of pumice with low abrasion loss and/or high absorption capacity has created a market for synthetic substitute materials. In theory, pumice powder or siliceous clays could be mixed with water, heated in ovens and converted to a bulk pumice product that could be sawed or crushed near textile manufacturing centers. Such a technology would reduce transportation costs by making ordinary domestic pumice deposits a suitable raw material. No longer would the textile industry be required to import natural foreign pumice. With the advent of this technology and increased environmental mitigation costs, production from sites such as the Benton Pumice Beds will likely come to an end.

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# Geology, Genesis and Mining of High Brightness, High Purity Limestone Deposits in the San Bernardino Mountains and Mojave Desert Area of Southern California

by  
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## ABSTRACT

High purity, high brightness limestone deposits in the San Bernardino Mountains and Mojave Desert region occur in upper Paleozoic carbonate rocks which are part of an upper Precambrian and Paleozoic sequence that unconformably overlies crystalline basement. The Paleozoic strata are divided into formations and members, and correlated with strata of the inner Cordilleran miogeocline. The region has been affected by multiple Mesozoic intrusive, contact, and regional metamorphic events. Structure is complex, and includes polyphase Mesozoic folding and thrusting, and complex Cenozoic structures. The area continues to be seismically active.

High brightness (white), high purity crystalline limestone deposits are uncommon because their formation is dependent on several geologic processes which include; 1) depositional environment, 2) contact and or regional metamorphism, 3) folding and faulting, 4) uplift and erosion, and 5) preservation through geologic time. The complex geologic history of the San Bernardino Mountains and Mojave Desert region has allowed the formation of several large high brightness, high purity limestone deposits which are currently being mined or will be mined in the future.

Specialty Minerals, Inc. (formerly Pfizer), Pluess-Staufer (California), Inc. and Partins Limestone, Inc. produce high brightness, high purity limestone from several quarries in the San Bernardino Mountains. These active mines combined with undeveloped deposits controlled by Pluess-Staufer in the San Bernardino Mountains, New York Mountains, and Bristol Mountains in the Mojave area, contain proven and or indicated reserves sufficient to sustain production through the 21st century.

Detailed geologic mapping, intimate knowledge of stratigraphy, recognition of complex structures, sampling, drilling and assay data, are proven tools in the discovery and delineation of high brightness, high purity limestone deposits in the San Bernardino Mountains and Mojave Desert region of southern California.

## INTRODUCTION

The San Bernardino Mountains and Mojave Desert area of southern California contain the largest high brightness, high purity limestone mining operations and undeveloped reserves in western North America (Figure 1). Combined annual production of high brightness limestone products from several open pit mines is approximately 1.5 million tons, with an estimated gross value of \$6 million dollars per year. Specialty Minerals Inc.

(formerly Pfizer Inc.), Pluess-Staufer (California), Inc., and Partins Limestone (Riverside Cement), are the major producers. An additional 5.0 million tons of cement grade limestone is mined by several large cement producers in the Mojave Desert area.

The purpose of this paper is to summarize the geologic setting and genesis of the white, high purity crystalline limestone deposits which are currently being mined, or will be mined in the future.

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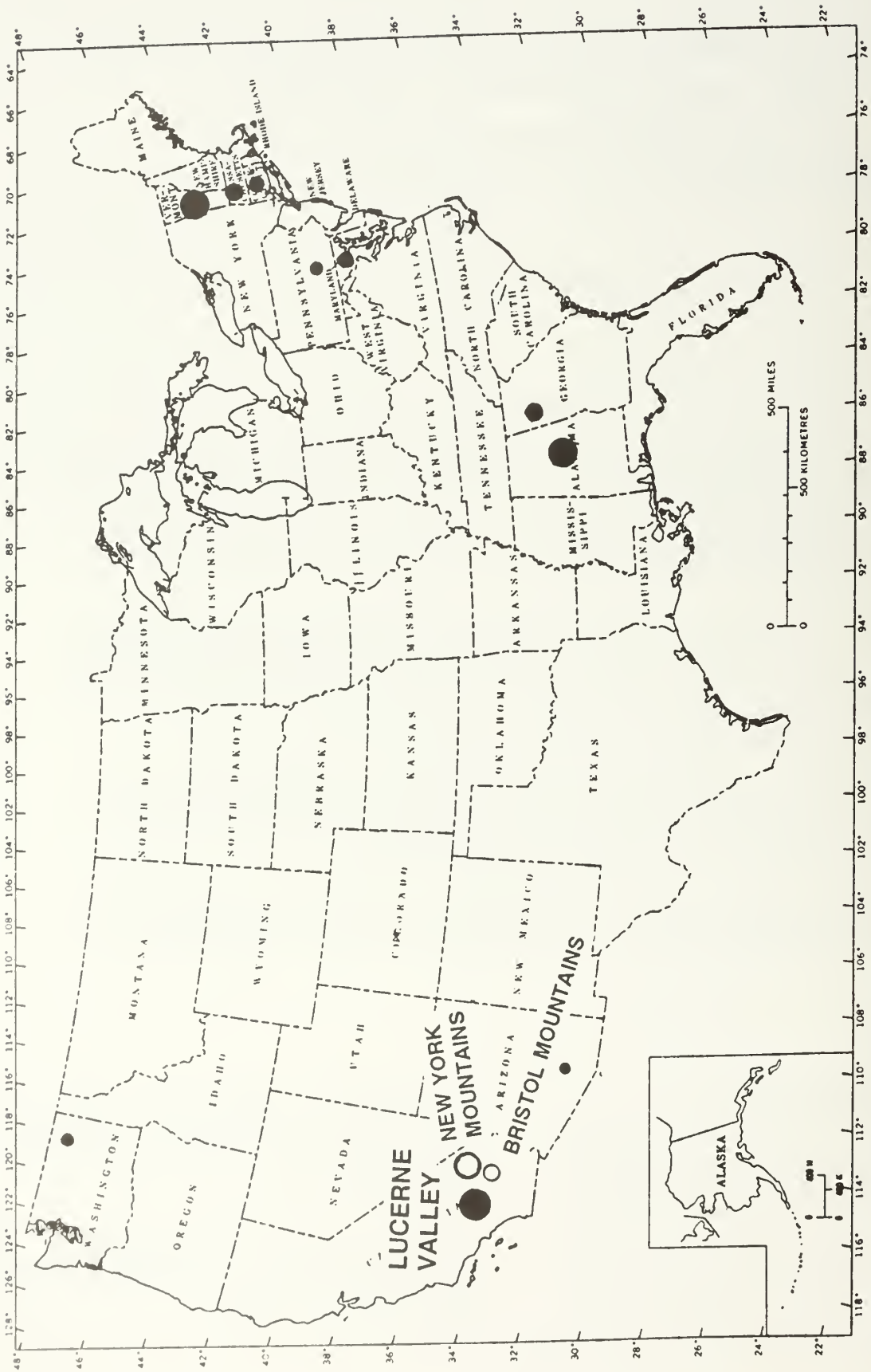


Figure 1. Major high brightness, high purity limestone producing areas in the United States. Size of dot indicates relative amount of production. Location of undeveloped New York Mountains deposits shown by open circle.

## REGIONAL GEOLOGIC SETTING

A variety of rocks of Precambrian to Recent age are exposed within the San Bernardino Mountains and Mojave Desert region. The late Precambrian and Paleozoic sedimentary rocks unconformably overlie earlier Precambrian basement. Three major facies, including cratonal, miogeoclinal, and deeper water marine strata, are recognized (Figure 2).

Paleozoic rocks exposed in the southeastern Mojave Desert are characterized by a thin, incomplete sequence of shallow marine cratonal strata (Figure 3). These sequences lack upper Precambrian sedimentary rocks, and are very similar to the classical cratonal section exposed in the Grand Canyon area (Stone and others, 1983). Paleozoic sequences in the central and western Mojave Desert and San Bernardino Mountains contain elements of both cratonal and miogeoclinal affinity (Figure 4). A major unconformity is present between Upper Cambrian and Devonian strata throughout the Mojave region. In the San Bernardino Mountains, upper Precambrian and Lower Cambrian rocks are of miogeoclinal aspect, Middle Cambrian strata are of cratonal aspect, and upper Paleozoic rocks are identical to inner miogeoclinal facies of the central and eastern Mojave region (Brown 1984).

High brightness, high purity crystalline limestone deposits occur in upper Paleozoic miogeoclinal limestone formations in several ranges in the San Bernardino Mountains and Mojave Desert.

In contrast to the shallow-water, carbonate-dominated, cratonal and miogeoclinal strata of the central Mojave and San Bernardino Mountains, are exotic strata of the "Northwestern Mojave Terrane" (Figure 2). Deep-water, siliceous clastic and volcanogenic strata of Precambrian through Permian age, and Mesozoic strata are exposed in several ranges, (Carr and others, 1984).

Rocks of the "Northwestern Mojave Terrane" are considered allochthonous, and display evidence of a major Paleozoic tectonic event, interpreted to be related to the Antler Orogeny of Mississippian age (Carr and others, 1984). Miogeoclinal-craton strata in the remainder of the Mojave Desert region show no evidence of Antler deformation. A major tectonic boundary is thought to separate miogeoclinal-craton strata from rocks of the "Northwestern Mojave Terrane" (Figure 2). This contact indicates facies and thickness trends of the miogeoclinal rocks and has juxtaposed the allochthonous deep water strata against them. Burchfiel and Davis (1972) proposed a major left-slip truncation event during Permian-Triassic time to juxtapose the facies.

Several major tectonic events have been recognized in various parts of the San Bernardino Mountains and Mojave Desert region. These include complex Mesozoic age polyphase folding and thrust faulting, contact and re-

gional metamorphism, and intrusive events. Cenozoic activity includes high and low-angle faults, mild folding, and abundant volcanism. The major province boundaries (San Andreas and Garlock fault zones) were formed and many ranges uplifted and eroded during Cenozoic time.

The Mojave area continues to be seismically active as evidenced by the large number of significant earthquakes in the area during 1992.

The complex geologic history of the San Bernardino Mountains and Mojave Desert region has allowed the formation of several large high brightness, high purity limestone deposits which are currently being mined or will be mined in the future.

## GENESIS OF WHITE HIGH CALCIUM LIMESTONE DEPOSITS IN THE MOJAVE AREA

Carbonate rocks are found extensively on all continents, but high purity, high brightness (white) limestone deposits are relatively uncommon in nature because their formation is dependent on the superposition of several independent geologic processes, acting over a long period of time. These geologic processes include:

- 1) Deposition of originally pure limestone in high energy agitated, shallow marine environment.
- 2) Post depositional changes including metamorphism and/or magmatic processes to bleach and recrystallize the rock, and disperse any impurities which may have been present.
- 3) Structural controls including folding, faulting and orogenic processes to place the rocks in desirable structural settings.
- 4) Uplift and erosion.
- 5) Preservation through geologic time.

Because all the geologic processes are required, deposits of high calcium white crystalline limestone are relatively uncommon in nature, and are vastly different from common limestone. Deposits of high purity, high brightness crystalline limestone suitable for high quality filler and extender applications are limited and only occur in restricted areas.

Within the southwestern United States, currently productive, and potentially productive deposits of white, high purity limestone are present in the San Bernardino Mountains and Mojave Desert region of southern California. The San Bernardino Mountains and Mojave Desert area contain several currently productive, and undeveloped white, high purity limestone deposits, and the area is by far the largest producing district in western North America.

In this section the various processes influencing the genesis of the deposits will be summarized.

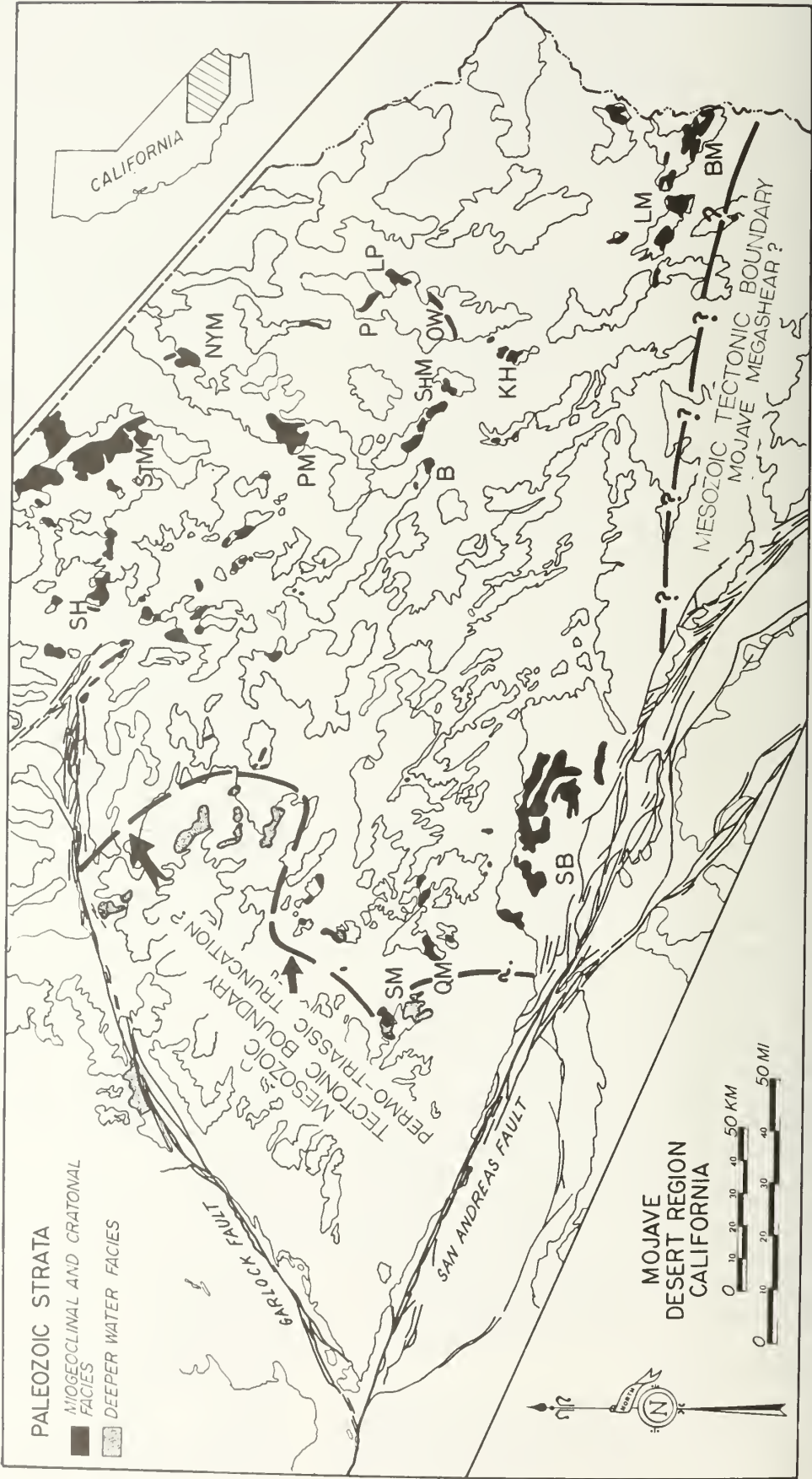


Figure 2. Map showing Paleozoic strata in the Mojave Desert region. SB = San Bernardino Mountains, SM = Shadow Mountains, QM = Quartzite Mountain, B = Bristol Mountains, ShM = Ship Mountains, P = Piute Mountains, LP = Little Piute Mountains, OW = Old Woman Mountains, KH = Kilbeck Hills, LM = Little Maria Mountains, BM = Big Maria Mountains, PM = Providence Mountains, NYM = New York Mountains, StM = Striped Mtn (Mescal Range), SM = Ship Mountains.



## CENTRAL AND WESTERN MOJAVE DESERT

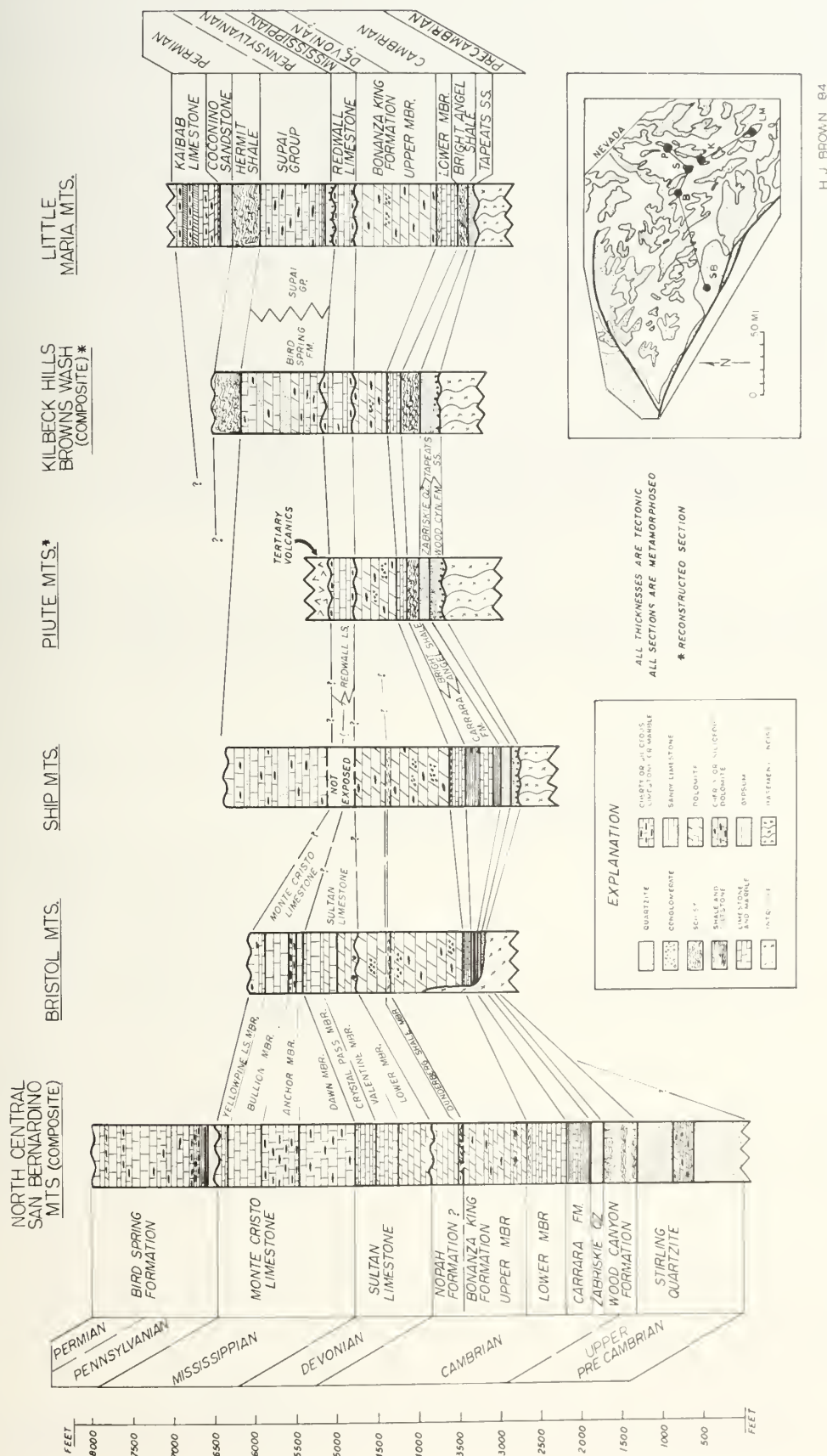


Figure 3. Correlation of metamorphosed Paleozoic strata from the San Bernardino Mountains to the southeastern Mojave region.

CORRELATION OF  
PALEOZOIC STRATA  
WESTERN, CENTRAL AND NORTHERN  
MOJAVE DESERT

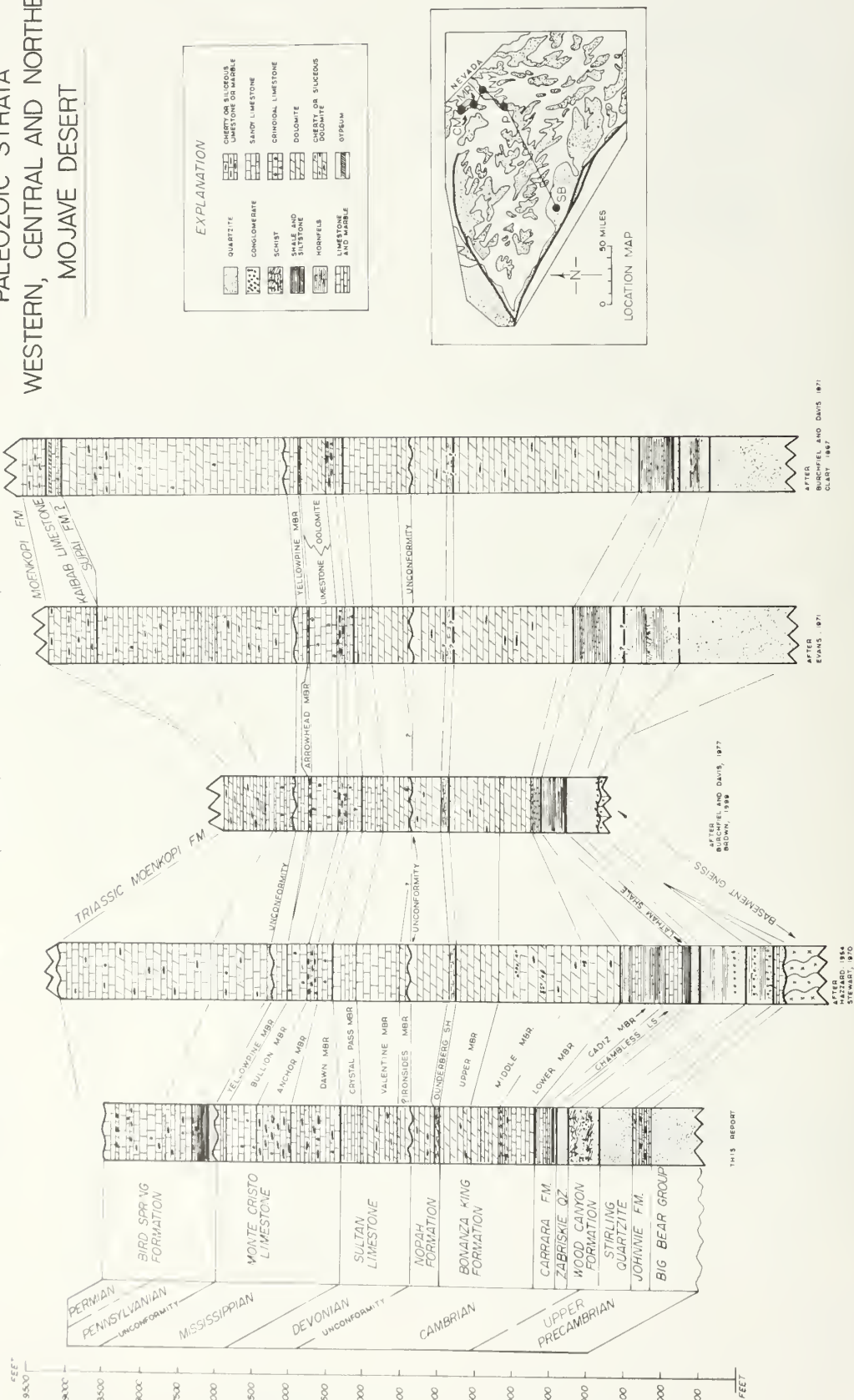


Figure 4. Correlation of Paleozoic strata from the San Bernardino Mountains to the northeastern Mojave region.

## ENVIRONMENT OF DEPOSITION

Environment of deposition is important because it determines the size, shape, purity, and other economically significant characteristics of the carbonate rock deposit.

Limestones that form in high energy environments generally contain only minor non-carbonate impurities, and are the source of high purity limestone. Limestones which form in low energy environments contain mud, clay, silica, and other impurities. Turbulent or agitated water will winnow mud from the sediments. Calm water allows mud to settle to the bottom and remain there.

Limestone formed in strongly agitated environments are characterized as being medium to coarse grained. The predominant sand sized grains are crinoid columnals, and lesser fragments of brachiopods and ostracods. Crinoids need well-aerated water of relatively high salinity. Sediments of this type accumulated in a shallow marine environment where vigorous winnowing currents were common.

A direct relationship exists between depositional environment and carbonate chemistry. Limestones which form in high energy environments contain more  $\text{CaCO}_3$ , and less  $\text{MgO}$ ,  $\text{Fe}_2\text{O}_3$ ,  $\text{SiO}_2$ , and  $\text{Al}_2\text{O}_3$  impurities than

muddy low energy limestones. In addition, a relationship exists between type of allochem present and chemical composition. Limestones containing abundant crinoidal debris generally have high  $\text{CaCO}_3$  and low  $\text{Al}_2\text{O}_3$  and  $\text{MgO}$  values. Crinoidal limestones which form in high energy shallow environments are the most economically favorable type of carbonate rocks.

Figure 5 is a ternary diagram showing chemical composition of various carbonate formations and members from the San Bernardino Mountains and Mojave Desert area. Note the high purity limestones in the bottom right corner formed in a high energy shallow marine environment. Within the San Bernardino Mountains and Mojave Desert area, are several cratonal-miogeoclinal Paleozoic rock formations which formed in a high-energy shallow marine environment. Formations which contain pure limestone include portions of the Bird Spring Formation (Pennsylvanian-Permian) Monte Cristo Limestone Bullion, Dawn Mbrs. (Mississippian), Redwall Limestone (Devonian), Sultan Limestone Crystal Pass Mbr (Cambrian), Bonanza King Fm. Upper Mbr (Cambrian), and Bonanza King Fm. Lower Mbr (Cambrian). Table 1 shows Paleozoic carbonate formations of economic interest as sources of high brightness high purity crystalline limestone in the San Bernardino Mountains and Mojave Desert area.

### EXPLANATION

AGE	FORMATION
△	PENN - BIRD SPRING FORMATION
■	MISS - MONTE CRISTO LS BULLION, DAWN MBRS.
■	DEV - REDWALL LIMESTONE
■	DEV - SULTAN LIMESTONE CRYSTAL PASS MBR
■	CAMB - BONANZA KING FM. UPPER MBR
○	CAMB - BONANZA KING FM. LOWER MBR
x	? UNCERTAIN

NO SAMPLES	LOCATION
65	SB, NY, S+M
350, 9	SB, B, NY, S+M
60	KH, P, LM, BM
50	NY, S+M, SB
20	SB, B, S+M. SHADOW(■)
33	SB, QM, B, SH, KH, P, OW, LM, BM, SH. SHADOW(●)
11	SB

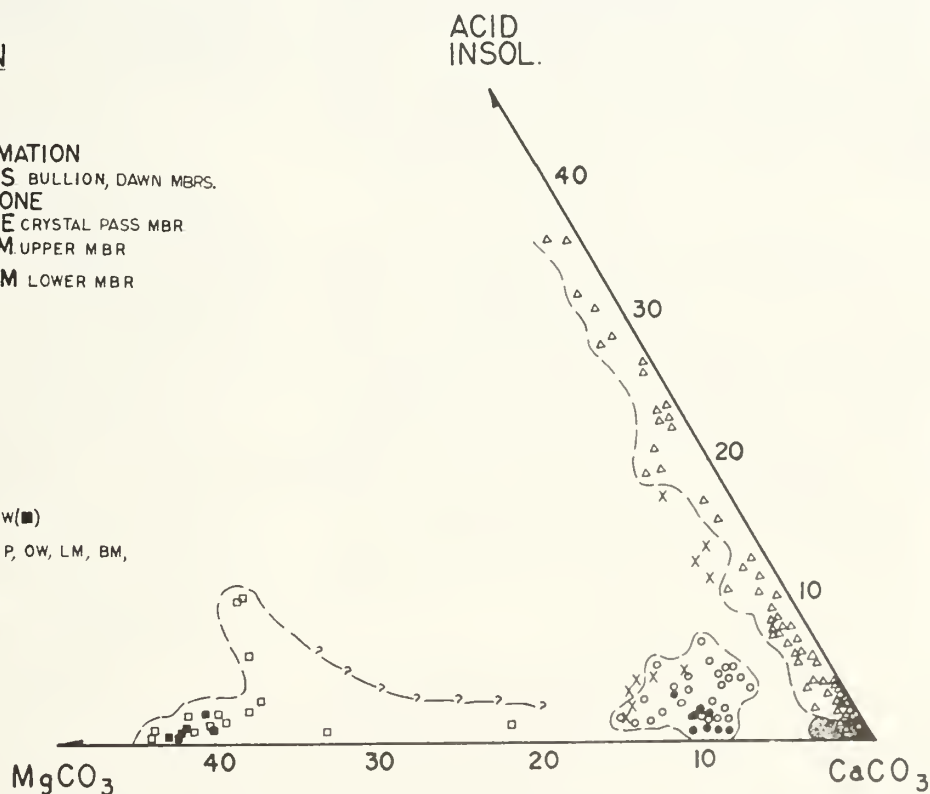


Figure 5. Ternary diagram showing the percentage of  $\text{CaCO}_3$ ,  $\text{MgCO}_3$ , and acid insolubles of Paleozoic cratonal and miogeoclinal carbonate strata in the San Bernardino Mountains and Mojave Desert region. See Figure 2 for explanation of abbreviations.



Table 1. Paleozoic formations of economic interest as potential sources of high brightness, high purity, crystalline limestone, San Bernardino Mountains and Mojave Desert area.

AGE	THICKNESS (FEET)	FORMATION/MEMBER, DESCRIPTION	LOCATION OF MAJOR DEPOSITS MOUNTAIN RANGE
PENNSYLVANIAN-PERMIAN (MIOGEOCLINAL)	UP TO 350 FEET	BIRD SPRING FORMATION (UNNAMED MEMBER) THIN TO MEDIUM BEDDED, MEDIUM TO COARSE GRAINED, WHITE CALCITE MARBLE. CONTAINS 2-7% SILICATE IMPURITIES, AND OCCASIONAL INTERBEDDED GREY AND BROWN LIMESTONE, SILTY LIMESTONE AND DOLOMITE LAYERS.	SAN BERNARDINO, NEW YORK MOUNTAINS BRISTOL MOUNTAINS MESCAL RANGE ALVORD MOUNTAINS
MISSISSIPPIAN (MIOGEOCLINAL)	UP TO 400 FEET	MONTE CRISTO LIMESTONE BULLION MEMBER THICK BEDDED TO MASSIVE, LIGHT GREY TO VERY WHITE, VERY PURE, CRYSTALLINE LIMESTONE AND COARSE GRAINED CALCITE MARBLE. CONTAINS ABUNDANT CRINOIDAL DEBRIS WHEN WEAKLY METAMORPHOSED.	SAN BERNARDINO, NEW YORK MOUNTAINS BRISTOL MOUNTAINS MESCAL RANGE
MISSISSIPPIAN (CRATONAL)	UP TO 200 FEET	REDWALL LIMESTONE MIDDLE MEMBER MEDIUM TO THICK BEDDED, WHITE, MEDIUM TO COARSE GRAINED CALCITE MARBLE. GENERALLY PURE, BUT CONTAINS UP TO 8% ORANGE AND GREEN SILICATE STREAKS, AND RED TO ORANGE IRON OXIDE STAIN ON FRACTURES.	BIG MARIA MOUNTAINS LITTLE MARIA MTNS PIUTE MOUNTAINS KILBECK HILLS
DEVONIAN (MIOGEOCLINAL)	UP TO 350 FEET	SULTAN LIMESTONE CRYSTAL PASS MEMBER MEDIUM TO THIN BEDDED, MEDIUM TO FINE GRAINED, WHITE, CALCITE MARBLE. CONTAINS SEVERAL INTERBEDS OF DARK GREY LIMESTONE AND OR DOLOMITE. WHITE MARBLE IS PURE, BUT CONTAINS COMMON IRON OXIDE STAIN ON BEDDING AND FRACTURE SURFACES.	SAN BERNARDINO MTN NEW YORK MOUNTAINS MESCAL RANGE

METAMORPHISM

Metamorphism is of great importance in the formation of many high purity, high brightness (white) limestone deposits. Metamorphism of limestones in proximity to igneous intrusions often results in the bleaching of susceptible rock, and coarsening of grain size. Regional metamorphism caused by pressure and heat at depth also causes the limestone to recrystallize, resulting in the coarsening of grain size, dispersion of impurities (if present), and bleaching or whitening of the rock.

Pure limestones formed in agitated water, when subjected to metamorphism may form very white, coarse grained, very pure calcite marble deposits of premium quality. Within most areas of the San Bernardino Mountains and Mojave Desert area the Paleozoic rocks have been subjected to regional and or contact metamorphism (Brown 1987). Formations or Members which have been recrystallized and bleached to white calcite marble include Devonian Sultan Limestone, Crystal Pass Member, Mississippian Monte Cristo Limestone Bullion Member, Mississippian Redwall Limestone Middle Member (cratonal facies), and portions of the Bird Spring Formation of Pennsylvanian-Permian age.

Cretaceous age regional metamorphism is variable in the Mojave but ranges from lower greenschist facies in the central Mojave up through amphibolite facies in the south-eastern Mojave. Paleozoic rocks in the San Bernardino Mountains have been metamorphosed to greenschist, amphibolite and in some areas to granulite facies (Brown 1991).

Intrusion of numerous plutons and batholithic rocks ranging from Permo-Triassic through Late Cretaceous age has resulted in contact metamorphism in many areas. Some limestone deposits have been affected by multiple metamorphic events and have been bleached and recrystallized to exceedingly coarse grained, very white calcite marble.

STRUCTURAL CONTROLS

Structural controls of carbonate deposits have an important influence on the formation of a deposit. Folding can strongly influence a deposit. Thickness may be increased in the core of folds, while the limbs may be significantly thinned. Faulting may also exercise strong influence on a deposit. Faults can truncate a deposit at shallow depth, or hide a vast deposit under shallow cover. Other faults may cause repetition or omission of a deposit.

As noted previously, Paleozoic rocks in the Mojave have undergone a complex deformational history which includes multiphase folding and faulting. Deposits therefore are often complexly folded and faulted.

UPLIFT, EROSION, AND PRESERVATION THROUGH GEOLOGIC TIME

Uplift and erosion have strong influence on the preservation and mining of a deposit. Prolonged erosion may completely remove a deposit, while more recent uplift and erosion may remove the overburden.

Paleozoic rocks in the Mojave area originally covered the region. Uplift during Tertiary time, and erosion have largely removed most of the Paleozoic rocks in the Mojave, leaving islands (remnants) of Paleozoic rocks in a sea of white and alluvium. Within some of the ranges are white marble deposits, several of which are quite extensive.

The San Bernardino Mountains were not uplifted until more recent (Plio-Pleistocene) time (May and Penning 1982), thus the roof pendants are more extensive, and several large deposits of white, crystalline limestone are present.

## USES AND SPECIFICATIONS OF HIGH BRIGHTNESS, HIGH PURITY LIMESTONE

High purity white crystalline limestones have a large number of uses and are classified as white fillers and extenders with value added characteristics. The products are finely ground, high brightness, high purity limestone, and are the whitest, purest, and most valuable per ton of limestone products.

Desirable characteristics are high brightness (white color), low tint, uniform fine particle size, freedom from dirt, and chemical purity. Color and purity are of utmost importance in virtually all applications. Limestone suitable for white fillers and extenders is limited to a mini-

mum of 98%  $\text{CaCO}_3$ , and a maximum of 2% combined  $\text{MgCO}_3$ ,  $\text{SiO}_2$ , and all other impurities combined. Brightness requirements range from low 90's to greater than 95. Tint values are generally below 2.0.

The greatest uses of fillers and extenders are in paint, rubber products, putty, pottery, paper, a variety of plastics, food, flooring, PVC pipe, white ink, tooth paste, wire coating, glue, caulking compounds, resins, and polyesters. Uses in the housing industry include ceiling and wall textures, dry wall mud, joint compounds, stucco, and fiberglass roofing shingles.

As can be seen, for most uses, white fillers and extenders require not only the most pure limestone, but also the whitest color of all limestones. The restricted nature of the deposits and the fact that products are shipped as far as 2,000 miles from the source, indicate a large demand by our society for these valuable products.

## HIGH-BRIGHTNESS LIMESTONE MINING OPERATIONS IN THE SAN BERNARDINO MOUNTAINS

Several large, open pit, white, crystalline limestone/calcite marble quarries and undeveloped deposits are present in the San Bernardino Mountains. Combined

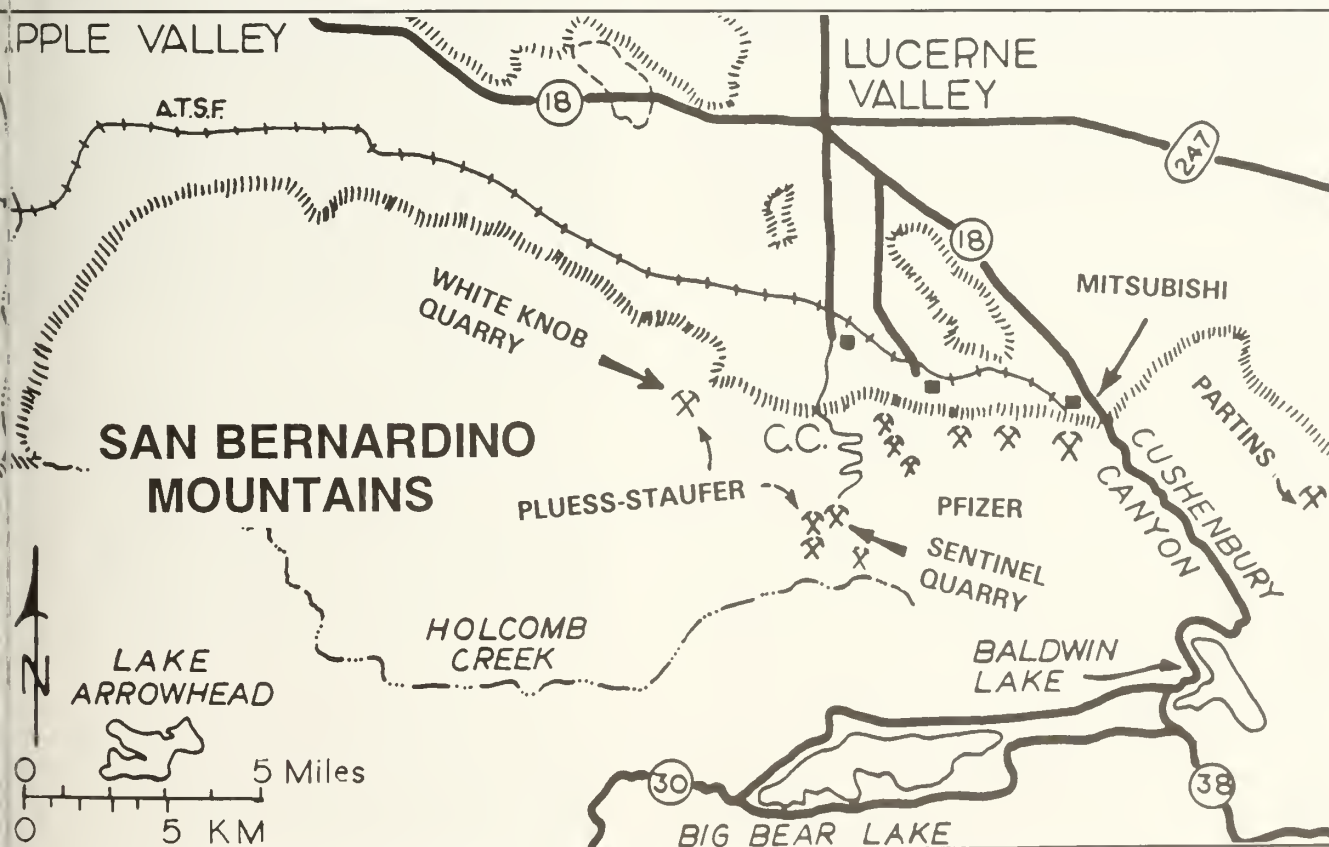


Figure 6. Map of the Lucerne Valley and San Bernardino Mountains area showing location of major limestone mining operations.



annual production is approximately 1.5 million tons with an estimated gross value of \$75 million dollars per year. Pfizer Inc., Pluess-Staufer (California), Inc., and Partins Limestone (Riverside Cement) are the major producers of white crystalline limestone products (Figure 6).

An estimated 5.0 million tons of cement-grade limestone is also mined by several large cement producers from the San Bernardino Mountains and Mojave Desert area.

### **Specialty Minerals, Inc. (Pfizer Inc.) Mining Operations**

The Specialty Minerals Inc. (formerly Pfizer Inc.) Lucerne Valley operation is the largest producer of high-brightness limestone products in the San Bernardino Mountains, and has been in continuous operation for 30 years.

During the 1960s and 1970s most ore came from the Nett Hill and Furnace quarries in Furnace Canyon. These multi-bench open pit quarries were developed in complexly folded, faulted and overturned Devonian Sultan Limestone Crystal Pass Member that had been metamorphosed to a medium-grained white calcite marble.

Since 1980 all ore has come from the Marble Canyon Quarry. This large quarry has been continuously mined by various operators since 1972. The ore body is composed of medium-grained white calcite marble of the Mississippian Monte Cristo limestone Bullion Member. This unit is multiply folded and generally steeply dipping, but overturned in the quarry area.

The Marble Canyon deposit is a multi-bench side hill quarry. Two to three working levels are operated at any one time to supply the rock needed to meet production requirements. The multi-working level concept allows for the blending of various rock qualities to meet the quality standards of Pfizer's customers.

The projected Marble Canyon deposit life is 20 years, depending on customer demand. Pfizer mined the Marble Canyon deposit continuously since 1980. Completion of mining activities will result in approximately twenty-three million (23,000,000) tons of ore and about nine million (9,000,000) tons of low-grade material and overburden having been removed from the quarry. On an annual basis, the long range plan for the Marble Canyon deposit calls for approximately 1,100,000 tons of combined ore and overburden to be removed each year for the next 20 years.

The Marble Canyon deposit has been mined using a bench height of 40-45 feet. The bench height is determined by factors relating predominantly to geology. The operating plan is designed with overall pit slopes of 45 to 50 degrees (about a 1:1 overall slope). The uppermost

bench in the Marble Canyon deposit is at the 5,600 ft elevation. The Marble Canyon deposit will ultimately have 15 to 16 benches, with the bottom elevation of the Marble Canyon Quarry at about the 4,900 foot level.

Blasted rock is loaded with a 13 cubic-yard wheel loader onto 85 ton trucks and hauled to the plant for crushing and processing. All crushing, screening, processing and milling facilities are located at the existing Marble Canyon Plant, about 3.5 miles to the northwest of the quarry at the base of the mountains in Lucerne Valley.

Specialty Minerals Inc. controls extensive undeveloped deposits of white marble formed from the Bullion Member of the Monte Cristo limestone, and Crystal Pass Member of the Sultan Limestone in the San Bernardino Mountains. Other undeveloped deposits in the Mojave area which Specialty Minerals Inc. controls may be mined in the future.

### **Pluess-Staufer (California), Inc. Mining Operations**

Pluess-Staufer (California), Inc. mines and processes high quality white limestone from extensive deposits in the San Bernardino Mountains, and is the second largest producer of high quality limestone fillers and extenders in the western United States. Currently active mines are located along the north range front and along the range crest. The processing plant is located in Lucerne Valley at the base of the mountains (Figure 6).

Pluess-Staufer (California), Inc. took over operations during the late 1970s and began an intensive, and ongoing, plant rebuilding and expansion program, as well as intensive and continuing geologic exploration and quarry development programs. Successful exploration and core drilling have discovered several new deposits, and proven sizable reserves at existing mines (Brown 1987). Existing proven minable and permitted reserves are adequate for well over 25 years.

Currently active mines are producing limestone from the Bullion Member of the Monte Cristo limestone of Mississippian age. The stratigraphic section at the Clau and Sentinel quarries is upright, while the White Knob Quarry is developed in an isoclinally folded and overturned section. At Sentinel Quarry the full thickness of the Bullion Member is present, and the deposit is up to 400 feet thick. The White Knob Quarry deposit occurs in the core of a tight fold and the thickness of the Bullion Member has been increased.

At the White Knob Quarry, rocks have been multiply metamorphosed to granulite facies, forming exceedingly coarse grained, very white translucent calcite marble. Individual calcite rhombs are commonly over 1 inch across.



Presently, ore is extracted from three quarries which have been developed into multi-bench open pit mines. Mining is accomplished by conventional methods. Ore is drilled and blasted and loaded by 13 cubic-yard front end loaders, into 50 and 85 ton rear dump haul trucks and trucked to the primary crushers. Primary crushers are located at the Sentinel and White Knob quarry sites. At the crushers, ore is crushed, screened and stockpiled by various quality grades. Combined crushing capacity is about 650 tons per hour. The crushed ore is hauled by 50 and 85 ton haul trucks, to the plant in Lucerne Valley at the base of the mountains.

At the plant, crushed ore is placed on the reclaim system by various quality grades. Rock enters the mill by a system of underground feeders and conveyors, and moves through Secondary and Tertiary crushing prior to Diamond Mill grinding, air classification, or ball mill grinding. The computer controlled grinding systems allow very precise grinding of the material to very narrow product specifications, or any specific specification a customer desires.

Pluess-Staufer produces a full range of coarse, fine, and ultra-fine grind, high brightness, high purity calcium carbonate products. Plant facilities offer both bulk and bagged materials in rail or truck quantities (Brown 1987).

### **Partins Limestone (Riverside Cement) Mining Operation (Cement) Mining Operation**

Partins Limestone (Riverside Cement) mines white calcite marble from a quarry east of Cushenbury Canyon along the range front (Figure 6). White marble has been mined for many years at this location. The moderately- to steeply-dipping, folded, white marble deposit occurs in the Bird Spring Formation of Pennsylvanian age (Brown 1986), and is about 40 to 50 feet thick. The rock is generally pure, medium-grained, white calcite marble. The main product produced is white swimming pool marble. Some of the rock is hauled to Crestmore and utilized for white cement.

### **Cement Grade Limestone Quarries**

Several large cement grade limestone quarry operations are present in the San Bernardino Mountains and Victorville area of the Mojave Desert. Combined production is estimated at 5.0 million tons per year.

Mitsubishi Cement mines cement grade limestone in a large quarry along the north range front of the San Bernardino Mountains (Figure 6). The Cushenbury Quarry was developed in dominantly grey marble, which is overlain by Pennsylvanian Bird Spring Formation (Brown 1986, Gantenbein 1986). Reserves are said to be adequate for 75 years.

Riverside Cement Company and Southwest Portland Cement Company mine large quantities of cement grade limestone from quarries in the Victorville area. Riverside Cement Co. obtains most of its production from the Sparkhule Hill Quarry near Quartzite Mountain (Figure 2), a large multi-level open pit mine developed in grey colored, metamorphosed upper Paleozoic marbles of the Bird Spring Formation of Pennsylvanian-Permian age.

Southwest Portland Cement Co. mines a large cement grade limestone deposit composed of the Triassic Fairview Valley Formation (MacIver 1984), a grey limestone conglomerate derived from erosion of the Bird Spring Formation.

### **Undeveloped Deposits in the Mojave Area**

Several significant undeveloped high brightness, high purity, crystalline limestone deposits are present in the Mojave area. Pluess-Staufer (California), Inc. controls several large high quality deposits in the New York Mountains and Bristol Mountains areas.

#### **New York Mountains**

Very large reserves of high quality limestone are present in the New York Mountains of eastern San Bernardino County, California. Detailed geologic studies, bulk sampling and limited core drilling, have defined nine major deposit areas on the Pluess-Staufer (California), Inc. claims (Figure 7).

Limestone deposits in the New York Mountains are developed in the Devonian Sultan Limestone Crystal Pass Member, Mississippian Monte Cristo Limestone Bullion Member, and Pennsylvanian Bird Spring Formation (Brown 1989).

Deposition of pure limestone, and subsequent Mesozoic age thrust faulting, folding, intrusion, metamorphism, and recrystallization and bleaching has formed several large white calcite marble deposits. Much of the limestone is very pure, containing >98% CaCO<sub>3</sub>, and is also of high brightness (88->95). The limestone is identical in quality to rock currently mined on a large scale in the San Bernardino Mountains, and is suitable for all currently produced ground limestone products. Combined reserves of the 9 deposit areas in the New York Mountains comprise the largest known undeveloped high brightness, high purity limestone reserve in the Southwestern United States (Brown 1989). Mining of these deposits may be impeded by pending California desert legislation which would place severe restrictions on mining in the area in which the deposits occur.

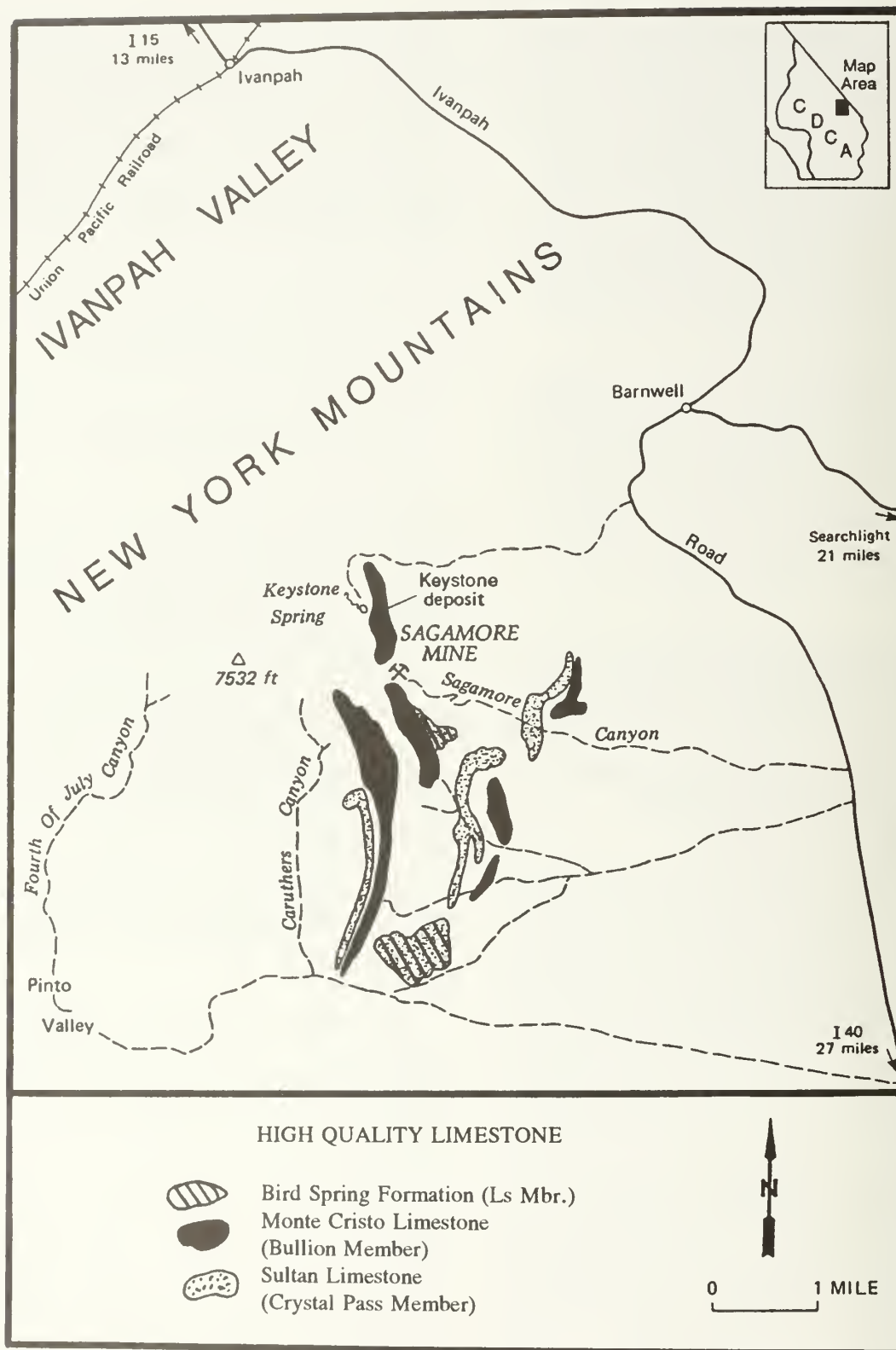


Figure 7. Location of high purity, high brightness limestone deposits in the New York Mountains (modified from Moyle and Cather, 1992).

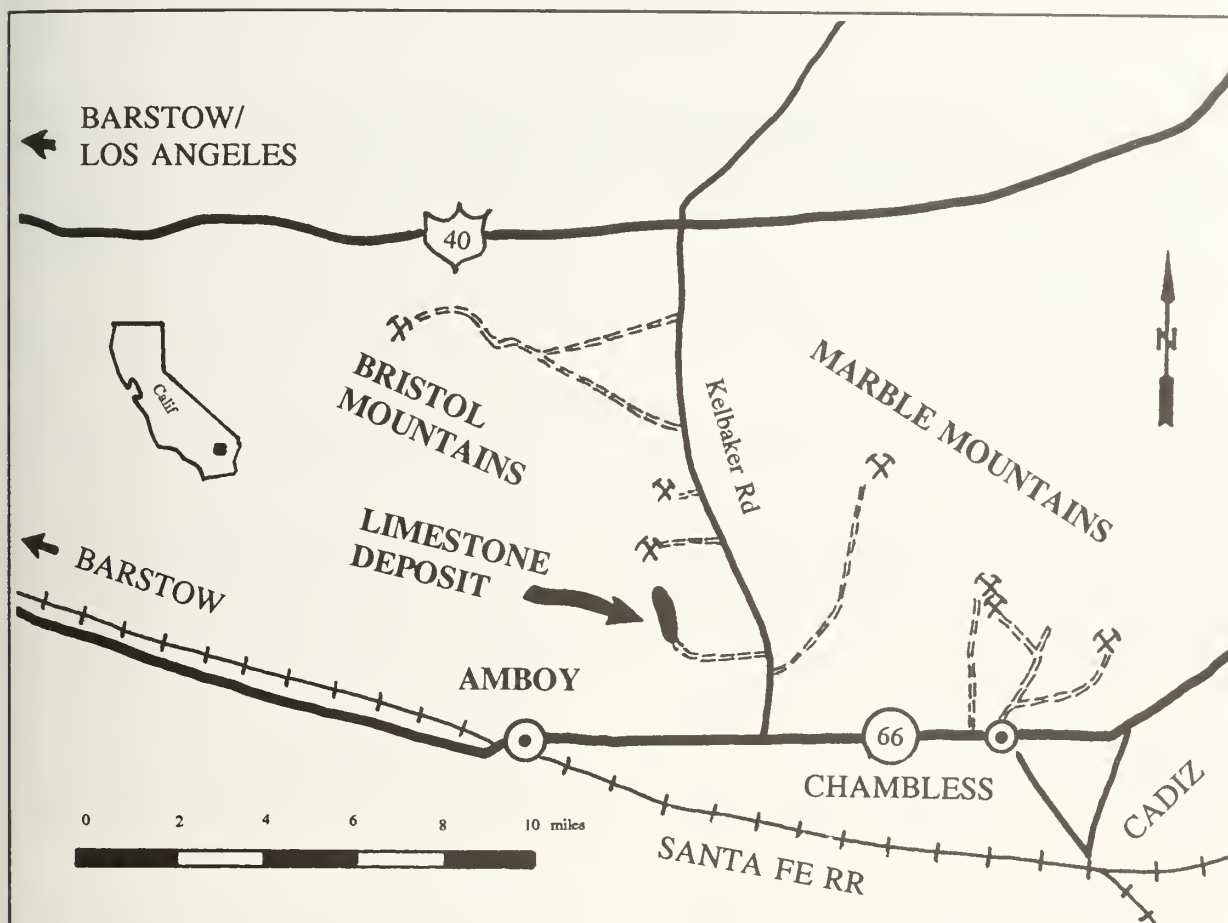


Figure 8. Location of high purity, high brightness limestone deposit in the Bristol Mountains near Amboy.

## Bristol Mountains

A large deposit of high brightness, high purity calcite marble is present in the Bristol Mountains near the town of Amboy (Figure 8). The deposit is owned by Pluess-Staufer (California), Inc. Detailed geologic mapping, bulk sampling and extensive core drilling have proven large reserves.

The deposit forms an extensive dip slope of Monte Limestone Bullion Member and is up to 300 feet thick. The originally pure limestone was folded, faulted, and metamorphosed multiple times, regionally and contact metamorphosed during Mesozoic time to form, very pure, coarse-grained white calcite marble (Brown 1981).

Uplift during Tertiary time, followed by erosion has removed most of the hanging wall. The deposit forms an extensive dip slope, well suited for mining with only minor overburden. This significant deposit will be developed in the future.

## CONCLUSIONS

The San Bernardino Mountains and Mojave Desert area of Southern California contain the largest high brightness, high purity limestone mining operations and undeveloped reserves in Western North America. Deposits have

formed in depositionally pure upper Paleozoic limestones, which have undergone multiphase Mesozoic deformation including intrusive events, and both contact and regional metamorphism. Structural history is complex, and the area continues to be seismically active. The complex geologic history of the region has allowed the formation of several large high brightness, high purity limestone deposits.

Detailed geologic mapping, intimate knowledge of stratigraphy, and recognition of complex structural relationships have proven to be invaluable tools in the exploration for, and the discovery of high-quality limestone deposits in the San Bernardino Mountains and Mojave Desert region. Rotary and core drilling, and abundant lab testing of surface, bulk and drill samples have proven effective in delineating ore continuity and quality.

The San Bernardino Mountains and Mojave Desert area has been, and will continue to be the largest source of high brightness, high purity calcium carbonate products in western North America.

## ACKNOWLEDGMENTS

Thanks are due to Pluess-Staufer (California), Inc. for permission to publish, and the conveners of the Forum for allowing me to participate.



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# Geology, and Processing Facility, CalMat Co. Reliance Plant, Irwindale, California

by

Edward D. Elkins<sup>1</sup> and Thomas E. Wiegert<sup>1</sup>

## ABSTRACT

CalMat Co. is one of the largest producers of construction aggregates in the United States. The CalMat Reliance plant is located in Irwindale, California, and is situated on an alluvial fan formed by the San Gabriel River. The fan deposits are of Quaternary age and were derived from granitic and metamorphic bedrock exposed in the San Gabriel Mountains to the north. The sediments are poorly sorted and range in size from large boulders to clay size particles. The coarse material is hard and durable and consists of quartz diorite, granodiorite, granitic gneiss, schist and minor amounts of volcanic rock. The matrix is comprised of silty sand with varying amounts of clay. Thin silt and clay lenses occur sporadically throughout the deposit. The clay content of the matrix and the degree of weathering of the coarse material increases with depth. Based on seismic data, the alluvial fan varies from 200 to 400 feet thick and overlies crystalline bedrock.

The Reliance plant was constructed in 1971 and 1972. It has a nominal capacity of 1200 to 1400 tons per hour, and typically produces more than three million tons of aggregate products per year. Alluvial fan sediments are mined from a gravel pit situated adjacent to the plant. The material is fed through a mobile, 48- by 60-inch, in-pit jaw crusher, then transported by conveyor to the main plant to be processed. The plant is modern and highly efficient. It has a typical wet and dry circuit and is capable of producing a wide range of aggregate products.

To extend the life of the plant, a 9,000 foot conveyor system is being constructed to connect it to a granite quarry operated by Azusa Rock Inc. The quarry is located north of Irwindale, and is 50 percent owned by CalMat Co. The conveyor will be used to export crushed rock from the quarry to Reliance. The existing plant will be modified to process the crushed rock.

## INTRODUCTION

CalMat Co. has been producing construction aggregate products since before 1929. The company is one of the largest producers of construction aggregates in the United States of America, with average annual aggregate production of 30 million tons per year. The CalMat Reliance plant is located in Irwindale, California (Figure 1), approximately 20 miles east of the city of Los Angeles. It was constructed in 1971 and 1972 and is situated on an alluvial fan deposited by the San Gabriel River.

The San Gabriel fan produces high quality aggregate and is the largest supplier of sand and gravel to the Los Angeles metropolitan area (Rushing, and Fife, D.L., 1982). The date that aggregate was first extracted from the fan is not known, however it was most likely prior to 1900 (Evans, and others, 1979). Total historical production from the fan probably exceeds 500 million tons. Currently, five major rock plants process aggregate derived from the fan. These include, Transit Mixed Concrete,

Livingston-Graham, United Rock Products, and CalMat Co.'s Reliance and Durbin plants (Figure 2).

The Livingston-Graham plant is reported to have a capacity of 3,000 tons per hour, while the others have production capacities in excess of 1,000 tons per hour (Kohler, and others, 1982). Several smaller plants, including Diversified Materials are also mining alluvial fan, or stream channel sediments. The five major aggregate producers have a combined extraction rate of 15 to 20 million tons per year. At that rate, existing, permitted reserves will probably be exhausted before the year 2005.

Azusa Rock and Owl Rock Products also operate rock plants in the area. Azusa Rock mines and processes granite and gneiss from a hard rock quarry located north of Azusa. Owl Rock Products operates a large plant in Azusa that currently imports and processes quarry-run material from Azusa Rock. Until recently, the Owl Rock plant mined rock and sand from a pit located near the head of the San Gabriel fan.

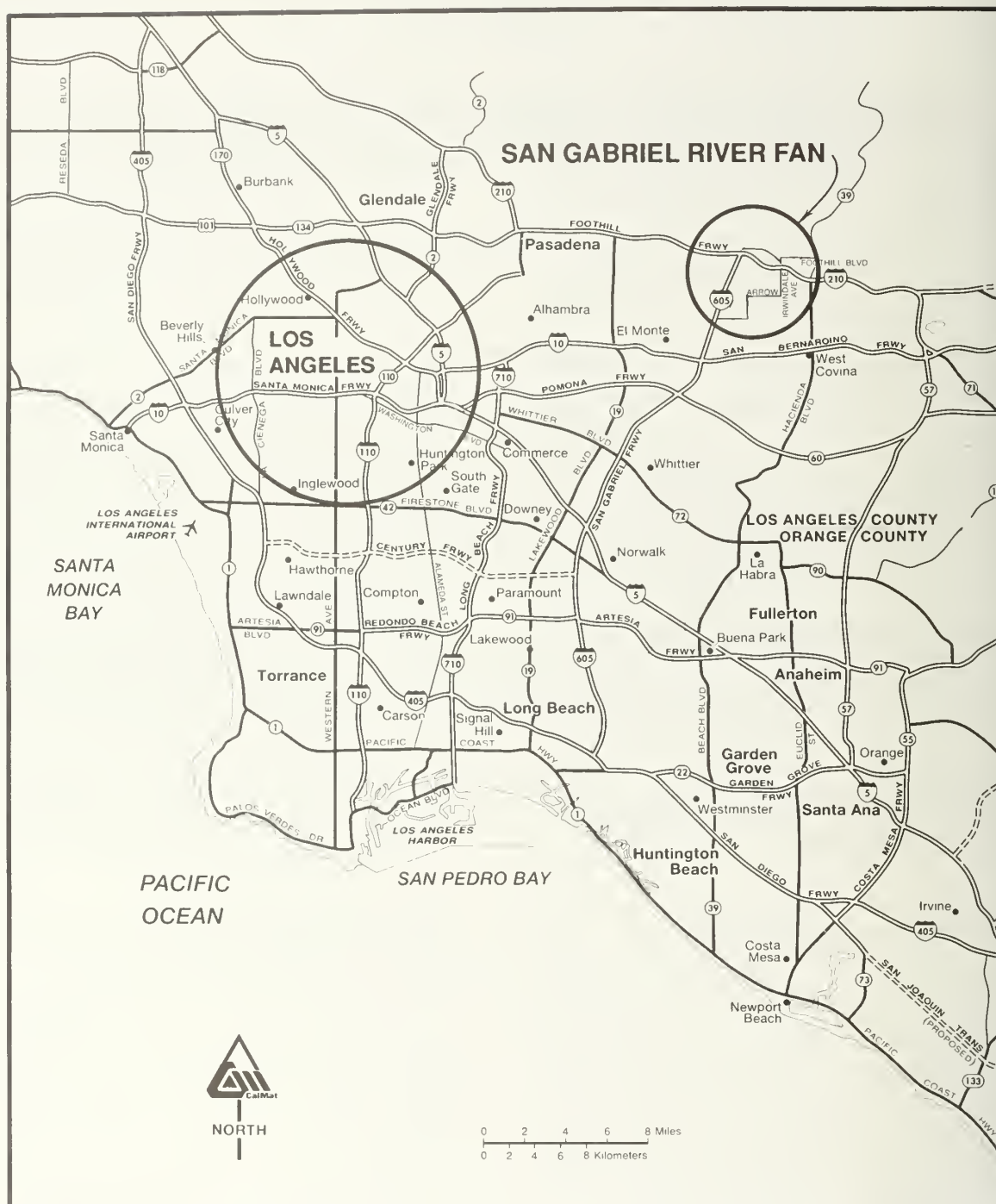
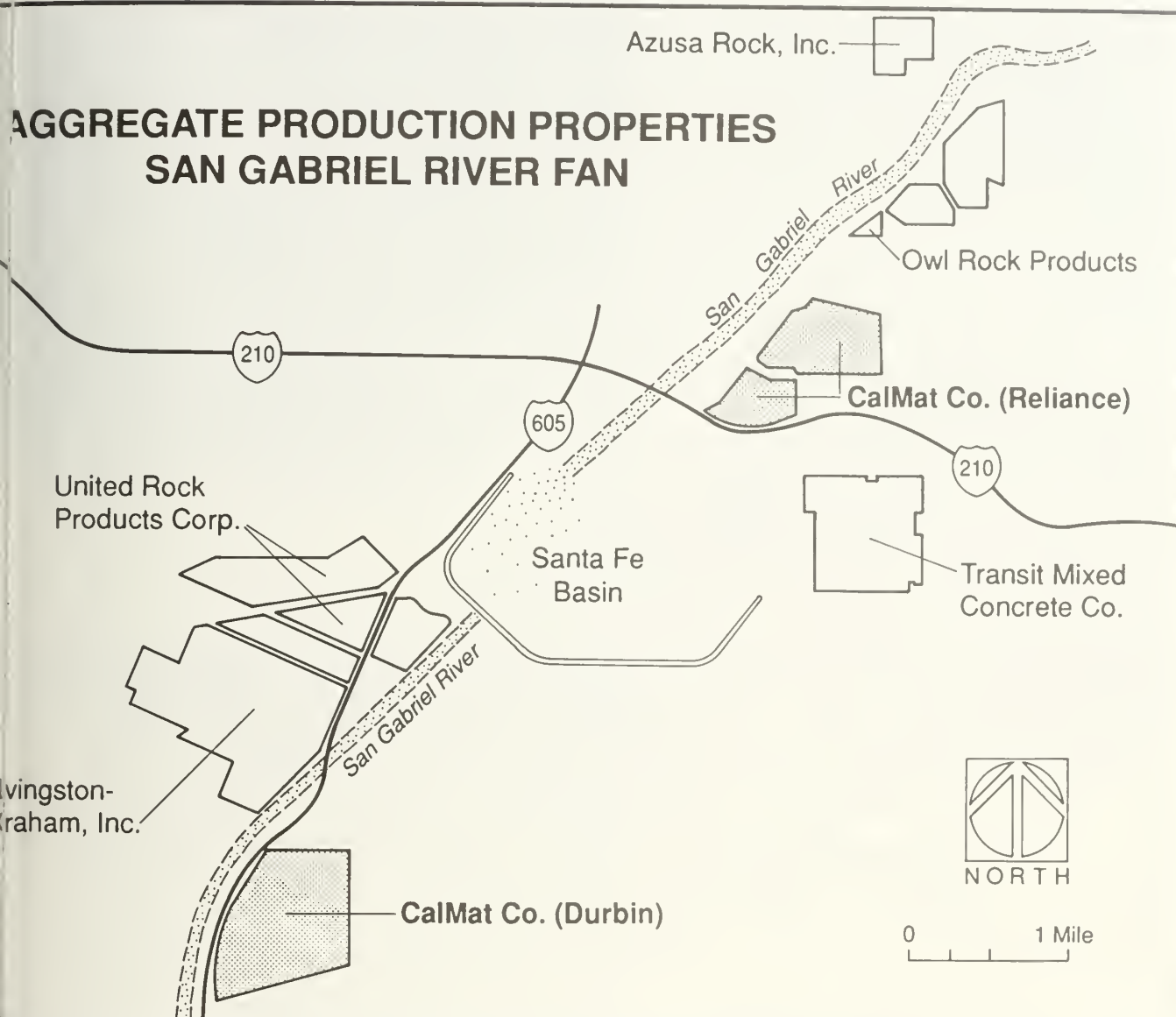


Figure 1. Index map showing location of the CalMat Co. Reliance plant and the San Gabriel River fan. The Reliance plant is situated 20 miles east of Los Angeles, California.





Map showing active aggregate producers on the San Gabriel fan (modified from Evans and others, 1979).

## GEOLOGY

Material mined at Reliance consists of alluvial fan sediments derived from crystalline bedrock of the San Gabriel Mountains (Figure 3). The mountains are part of the transverse ranges and extend approximately 50 miles east-west and 10 miles north-south. The sediments were deposited by the San Gabriel River, which drains an area of approximately 1,000 square miles.

Igneous rocks and gneiss are the principal rock types within the drainage area. Gneiss is the most prevalent lithologic rock in the San Gabriel Mountains (Dibblee, 1969). The gneiss is normally dark gray to black and contains amphibolite facies mineralogy composed mostly of plagioclase, biotite, and/or hornblende. The gneiss is typically layered with alternating bands of quartz-feldspar,

biotite, or biotite and/or hornblende (Saul, 1976). Gneiss in the central San Gabriel Mountains is thought to be of Precambrian age, but has not been dated (Ehlig, 1975).

Morton (1973), also identified cataclastic gneiss in the San Gabriel River drainage. According to Morton, the cataclastic gneiss is dark green, fine grained and consists of partly altered biotite and plagioclase with minor amounts of white mica and strained quartz.

Diamond drill holes completed on the Azusa Rock property, reveal the gneiss to be highly fractured, with hornblende and biotite altered in part to chlorite. The gneiss is moderately weathered overall, and strongly weathered along fractures. The fractures also contain abundant iron oxide staining and secondary mineralization.

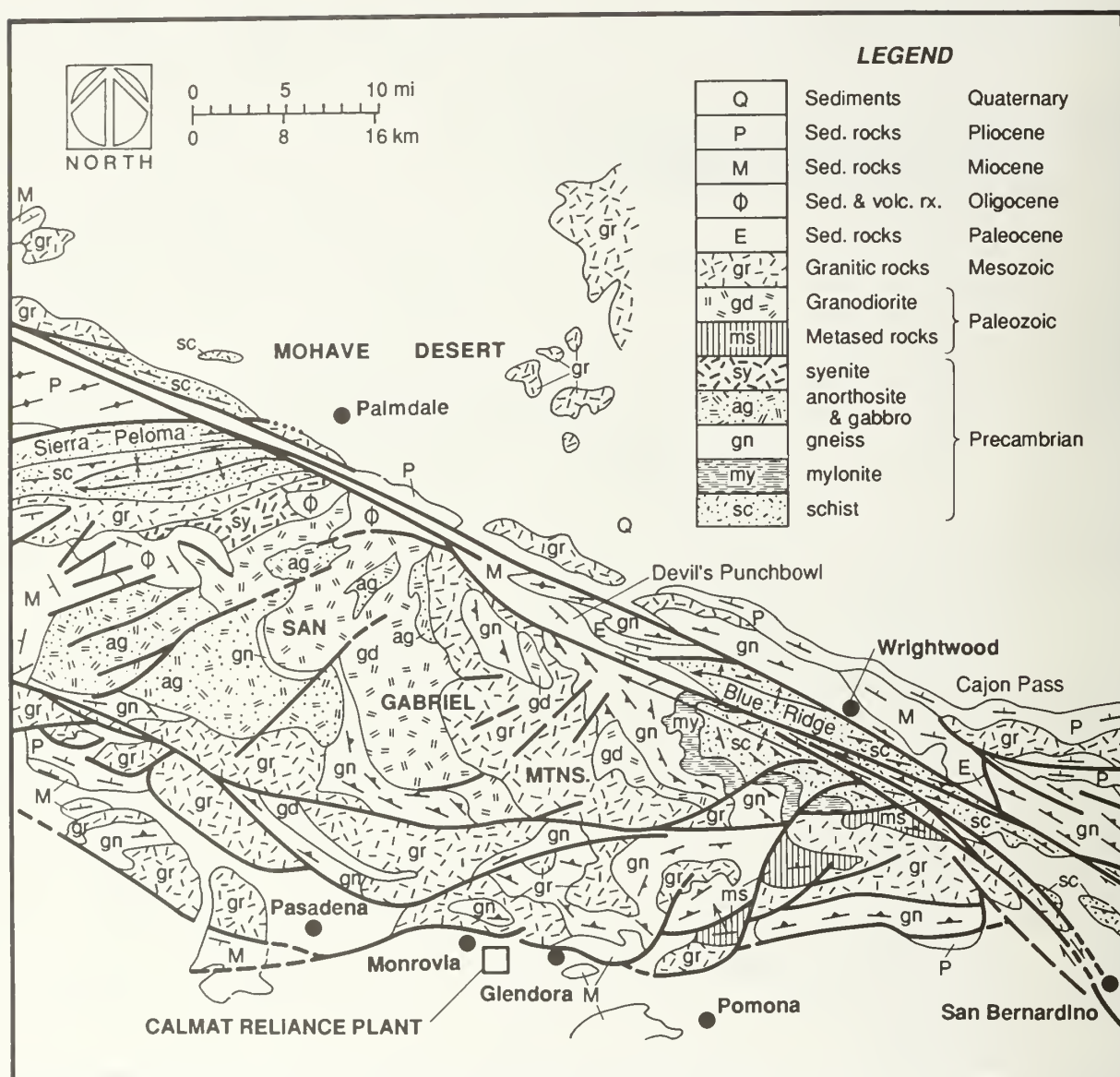


Figure 3. Generalized geologic map of the San Gabriel Mountains (modified from Dibblee, 1982).

The most common rock type in the San Gabriel River drainage is a late Mesozoic quartz diorite (Wilson Diorite of Miller, 1934). The rock is medium- to coarse-grained with massive to gneissic texture which locally grades to granodiorite or quartz monzonite. Mineralogically, most of the rock is biotite-hornblende or hornblende-biotite quartz diorite (Morton, 1973). In most areas, the rock is thoroughly fractured with epidote mineralization filling or coating fractures (Saul, 1976, Morton 1973). In addition, talc, sulfide, manganese and iron oxide mineralization occurs along fractures. Dark colored, ellipsoidal inclusions and gneiss xenoliths are also common in the quartz diorite.

Light granite and pegmatite, as well as hypabyssal dacite and basaltic dikes are common in gneiss and quartz

diorite. The dikes range from several inches to over 10 feet thick. They are generally discontinuous in length and irregular along strike. When encountered in the Azusa Rock diamond drill core, the dikes frequently contained sulfide mineralization and gouge or slickensides along at least one contact with the basement rock.

The Reliance pit is located less than one-half mile east of the current San Gabriel River channel (Photo 1). Elevation at the edge of the pit is about 600 feet above mean sea level (msl). Recent alluvial fan and San Gabriel Formation(?) deposits are mined at the site. The youngest alluvial fan deposits are 30- to 50-feet thick and contain unconsolidated, rounded to well rounded, cobbles and boulders in a gray silty sand matrix. The sediments are poorly sorted and range in size from large boulders to





Photo 1. The CalMat Co. Reliance plant is situated near the current San Gabriel River channel. Aggregate is mined from the pit situated adjacent to the plant. The photograph looks toward the east.



Photo 2. Alluvial fan deposits exposed in the east end of the Reliance pit. The sediments are poorly sorted, ranging in size from clay particles to boulders. The boulders are invariably of granitic origin.

size particles (Photo 2). Sporadic clay and silt lenses up to several feet thick occur throughout the deposit. The coarse material is hard and durable and consists mostly of quartz diorite, granodiorite, granitic gneiss, schist and minor amounts of volcanic rock. The large boulders, invariably are of granitic origin.

The recent sediments overlie older alluvial fan deposits of the San Dimas Formation. An abrupt scour and fill contact separates the two alluvial fan deposits. The contact is marked by a change in color, an increase in clay content, and increased weathering of the individual rock clasts. The San Dimas Formation is of late Pleistocene age, and generally consists of reddish brown, poorly bedded, poorly consolidated, rock, gravel and sand in a silty clay matrix (Morton, 1973).

Clay content and degree of weathering increases with depth at the Reliance pit because of the presence of the San Dimas Formation. The higher clay content and degree of weathering has had a negative impact on aggregate quality. Table 1 shows an example of the decline in aggregate quality since 1976. The higher L.A. Rattler results shown for 1992 are caused by the increased weathering of the San Dimas Formation, while lower Sand Equivalence (SE) is caused by its higher clay content.

Table 1. Comparison of Reliance materials, 1976 and present.

	1976 Average	1992 Average
<b>Material: 3/8" Gravel</b>		
Specific Gravity (ASTM C-127)	2.65	2.66
Absorption (ASTM C-127)	1.5	1.5
LA Rattler (ASTM C-131)		
100 Revolutions	6.6	10.4
500 Revolutions	30.6	36.9
<b>Material: Washed Concrete Sand (WCS)</b>		
Specific Gravity (ASTM C-128)	2.67	2.61
Absorption (ASTM C-128)	1.3	1.8
Sand Equivalence (SE) (ASTM D-2419)	85	81

Seismic refraction data indicates that the recent and older alluvial fan deposits overlie crystalline bedrock and that they are 200 to 400 feet thick in the vicinity of the Reliance pit (Ryland Associates, Inc., 1990). The configuration of the bedrock appears to be rather complex, consisting of a graben situated between two branches of the Duarte Fault (Ryland Associates, Inc., 1990 and Law Environmental, Inc., 1990). Bedrock appar-





Photo 3. After reserves are depleted, the Reliance plant will import crushed rock from a quarry operated by Azusa Rock Inc. The quarry can be seen in the foothills above the Reliance plant. The photograph looks toward the northeast.

ently forms a deep, northwest-southeast trending, linear basin that becomes shallower to the north and south.

When the existing Reliance reserves are depleted, the plant will import and process crushed rock from the Azusa Rock quarry (Photo 3). Azusa Rock, Inc., is jointly owned by CalMat Co. and Owl Rock Products, Inc. The quarry mines gneiss and granite, which is highly fractured, and has been intruded by numerous dacite, basalt, pegmatite and light granite dikes. A small outcrop of marble is situated at the top of the quarry. Since the rock is highly fractured, drilling and blasting is usually not required. Most mining is accomplished using a Caterpillar D-10 or D-11 bulldozer with a single shank ripper.

RELiance PLANT

The CalMat Reliance plant is a modern aggregate processing facility with a rated capacity of 1,200 to 1,400 tons per hour. The plant has average annual sales of 3 million tons per year. It was designed by the CalMat Co. Engineering Department and was built during 1971 and 1972. The plant consists of a central tower which uses gravity flow to the greatest extent possible. It is situated adjacent to the gravel pit from which the alluvial fan material is mined (Photo 1). The pit is located in both the city of Azusa and the city of Irwindale. The approved reclamation plan for the pit allows for 50-foot setbacks from property lines and 1:1 pit slopes. Depth of excavation is not limited in Azusa, but is limited to 200 feet below the surface in Irwindale. General information concerning plant and pit equipment is shown in Tables 2 and 3.

Pit Operations

A bank drag (a steel plate with ripper teeth) is dragged up and down the pit face to produce a homogenous run of material at the toe of the pit. The dragged material is loaded into a portable hopper and magnetic feeder by a large electric shovel. A 60-inch wide electro-magnetic feeder transfers the pit run material onto a 100-horsepower, 72-inch wide, by 120-foot long pendulum conveyor. The pendulum conveyor then dumps onto a 5-foot by 16-foot Simplicity vibrating grizzly feed. Minus 8-inch material passes through the grizzly and is plus 8-inch fraction is crushed by a 48-inch by 60-inch Buchanan jaw crusher set

an 8- to 10-inch closed-side setting. The crushed rock output along with the material passing through the grizzly are recombined on a 54-inch wide, under-jaw belt and are conveyed to the pit conveyor system.

Table 2. General information, CalMat Reliance plant.

Height	195 feet
Rated Capacity:	1,400 tons per hour (maximum)
Total Connected Horsepower	Approx. 7,000
Surge Pile Live Storage:	12,000 tons
Product Live Storage:	10,000 tons (over truck scales)

Table 3. Major pit excavation and crushing equipment.

Equipment	Type
Shovel:	9 1/2 yard Bucyrus-Erie 190-B 4160 volt, 450 HP
Bankdrag:	American 997C
Crusher car:	48" x 60" Buchanan Jaw crusher

The crusher car (Photo 4) was designed and constructed by CalMat personnel. The total weight of the crusher car including machinery is approximately 200 tons. When built, it was one of the largest rubber-tired mobile pit crushers in the world. It rests on four, hydro-

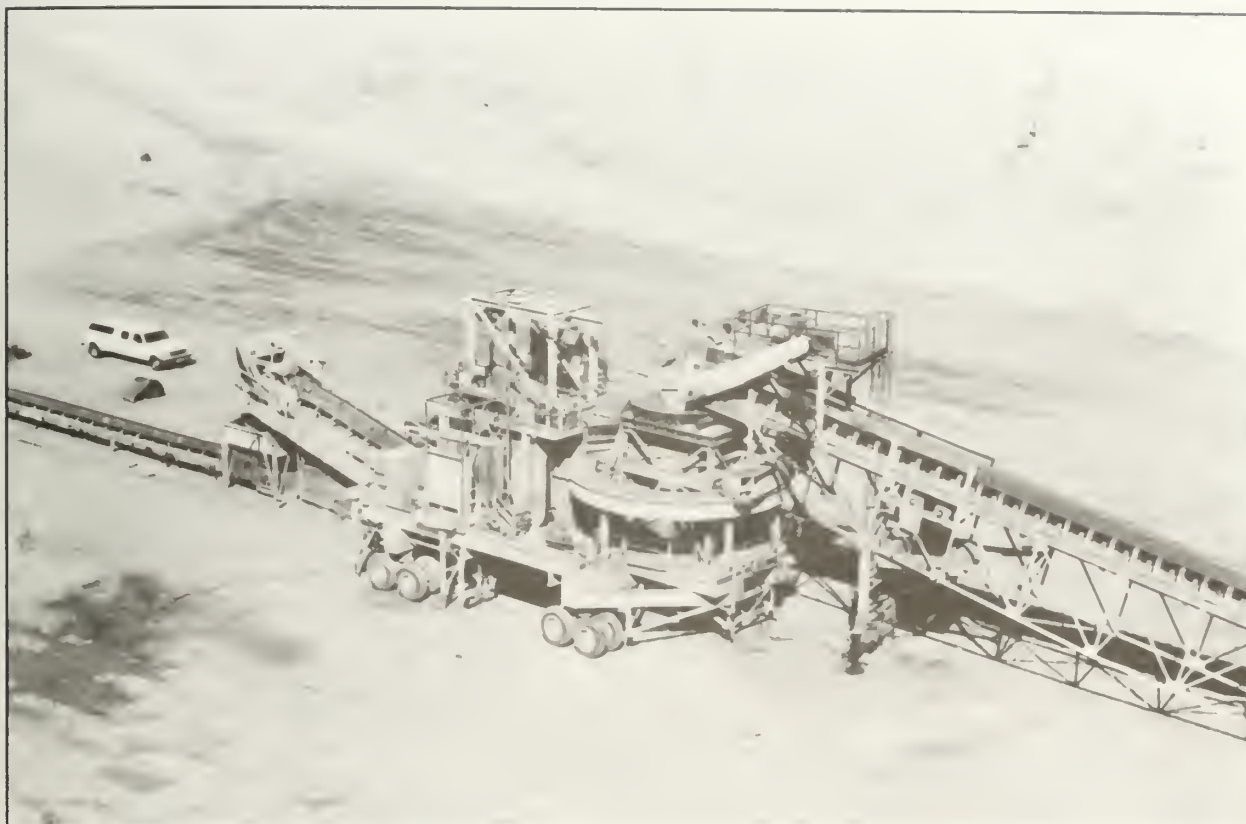


Photo 4. The Reliance crusher car was designed and constructed by CalMat Co. personnel. It contains a 48-inch by 60-inch Buchanan jaw crusher and weighs 270 tons. The tires, wheels and axles on the crusher car are from a B-29 bomber.



Photo 5. Participants of the 29th Forum on the Geology of Industrial Minerals inspect mining operations at the CalMat Co. Reliance gravel pit. The troupe was part of a tour organized by the forum that visited the property on April 27th, 1993.

lically operated steel pedestals during operation. The car is moved by lowering it onto the pneumatic tires and towing it with a Caterpillar 724 rubber-tired bulldozer. Repositioning the pendulum conveyor is normally accomplished in two hours or less. Moving the crusher car 100-feet ahead, usually takes two days or less. The amount of pit material excavated during each crusher move varies with the height of bank being worked. For a 100-foot high bank, the amount of material excavated is approximately 280,000 tons per move.

The pit conveyor system, is 42-inches wide and approximately 4000 feet long. It transports minus 10-inch material from the pit to a large surge pile located adjacent to the plant (Photo 5).



## Plant Equipment

The surge pile has a live storage capacity of approximately 12,000 tons. The surge pile tunnel is made of reinforced concrete and is 11 feet square inside by 132 feet long. The tunnel contains a 60-inch, *Syntron* F-88 feeder and a 42-inch wide discharge conveyor belt. Surge pile material is scalped by two 6-foot by 16-foot, 2-deck bull screens. The large oversize fraction (plus 3-inch) is fed to a 7-foot standard cone crusher and the smaller oversize (minus 3-inch, plus 7/8-inch) goes to two 7-foot shorthead crushers. The minus 1 1/2-inch naturals are routed to the sand and gravel side of the main processing mill.

In addition to the crushers mentioned above, the crushed rock side of the mill consists of ten 5-foot by 16-foot *Symon Bros.* 2-deck separation screens. The individual rock sizes are separated by the screens and recombined by a splitter gate system to make custom blends of a wide variety of crushed rock products. Oversize is routed back to the shorthead crushers and/or is stored in the bunker system to be recrushed later.

The sand and gravel (natural) side of the Reliance plant starts with a 8-foot diameter *Bodinson* twin shell scrubber. The natural sand and gravels are washed and separated in the scrubber. Finish sizing of the gravels is done on two *Symon Bros.* 5-foot by 16-foot, 2-deck screens, and two *Symon Bros.* 5-foot by 14-foot single deck screens. The sand is classified by an *Eagle* 10-foot by 36-foot dial-split sand tank and dewatered by two *Eagle* twin 54-inch sand screws.

Plant wash water is provided by a single 750 horsepower deep well. Plant waste water is cleaned and recycled by two *Jadair* clarifiers. The plant water requirement is approximately 3,000 gallons per minute, of which 75 to 80 percent is recycled water from the clarifiers.

The overhead bunker system has a live storage of 10,000 tons. The Reliance plant has a custom base blending system that allows the manufacture of specification base materials from the crushed rock products in precisely controlled proportions. Base can be blended from the materials held in the overhead bunkers at a rate of 1,000 tons per hour.

All products in the mill are loaded while the trucks are on the scales. Light weight and loaded weight are taken without moving the truck. The weigh master can then insure that each truck is fully loaded to legal capacity but not overloaded. These scales are 190 feet long and were the first scales of this size certified in United States.

When Azusa Rock quarry-run material is exported the Reliance plant, it will be 100 percent crushed stone containing no natural sand and gravel. In order to handle the change in feed, several modifications will be made to the Reliance plant. A 7-foot shorthead cone crusher and/or a vertical shaft impact crusher will be installed to create additional fines to augment those in the Azusa Rock feed. To handle the larger volume of crushed rock, two additional screens are to be installed in the main mill.

The plant already has the capability to shift crushed rock to the washed gravel side of the mill. This capability will be used extensively with the Azusa rock raw material in order to balance the plant's production with market demand.

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# **The Soledad Canyon ilmenite Mine (P.W. Gillibrand Co.) San Gabriel Mountains, Southern California**

by  
John C. Heter<sup>1</sup>

## **INTRODUCTION**

The P.W. Gillibrand Company holds 705 placer and lode claims in the Precambrian San Gabriel Anorthosite Complex of the western San Gabriel Mountains. These claims contain large tonnages of ilmenite, magnetite and apatite with anomalous quantities of zirconium (zircon), niobium, vanadium and rare earth elements.

Stockpiling of heavy mineral concentrates associated with aggregate mining from alluvial pits has occurred since 1984. The limited reserves of material from these alluvial deposits and their relatively low heavy mineral grades caused Gillibrand Company to initiate an extensive drilling and exploration program to develop the rock resources of ilmenite, apatite and magnetite.

Surface sampling identified three potential target areas. In 1986 a percussion drilling program was undertaken as a preliminary step in determining the resource potential of the three target areas. By 1987 and 1988, the company changed to a BX size diamond drilling program.

The drilling exploration program delineated approximately twenty million tons of combined heavy minerals (ilmenite + apatite + magnetite) in the target areas.

Production scale processing of the heavy minerals has started since 1984 with more than 20,000 tons of coarse ilmenite sold in 1990 to the export market for titanium pigment production.

## **LOCATION**

The P.W. Gillibrand Company claims are located in townships 3 and 4 North, Range 14 West, San Bernardino County and Meridian of the Sunland, Mint Canyon and Agua Fria 7.5 minute USGS quadrangles. The overall P.W. Gillibrand Company mineral ownership encompasses 674 lode claims and 31 overlapping lode claims (Figures 1 and 2). These holdings cover 13, 480 acres within the boundary of the Angeles National Forest, representing a

surface area of 21 square miles. The mine area is situated on the western margin of the San Gabriel Mountains, ten miles north of San Fernando Valley and one mile south of State Highway 14, the Antelope Valley Freeway, between Solemint and Acton.

## **HISTORY**

California's first gold rush was a result of a gold discovery in March 1842, in Placerita Canyon located only a few miles to the southwest of the claim area. Many gold and silver discoveries were made during the following years, particularly in Soledad Canyon on the north side of the range and in the east fork of the San Gabriel river on the southeast side of the range.

After the rock surface placers were mined out in the 1870's, large stamp mills were built as quartz mines became the principal source of gold (Clark, 1982). Many of these mines were worked through the depression years up to World War II when all the mines were idle.

Several attempts have been made to utilize the ilmenite-magnetite ore from the hard rock and derived gravels of the San Gabriel anorthosite complex (Oakeshott, 1958). The refractory nature of the titanium bearing ore foiled an attempt to extract iron by a company in Soledad Canyon in 1906.

The Mineral Increment Co. operated the Iron Blossom mine, (Claim Group II Area, Figure 3) where 10,013 tons of ore was mined in 1927-28 and used to manufacture paint base. The most extensive prospecting of the area was done by E.I. du Pont de Nemours and Co. between 1928 and 1938. They dropped their interests after more easily mined sources of titanium sand were developed in Florida. Between 1944 and 1952, Challoner Thompson extracted ilmenite and magnetite concentrate from placer sands in Sand Canyon. An ilmenite concentrate containing 59% ilmenite and 16% magnetite was sold as roofing granules and pigment plant feed.

<sup>1</sup> Technical Director, P.W. Gillibrand Co.

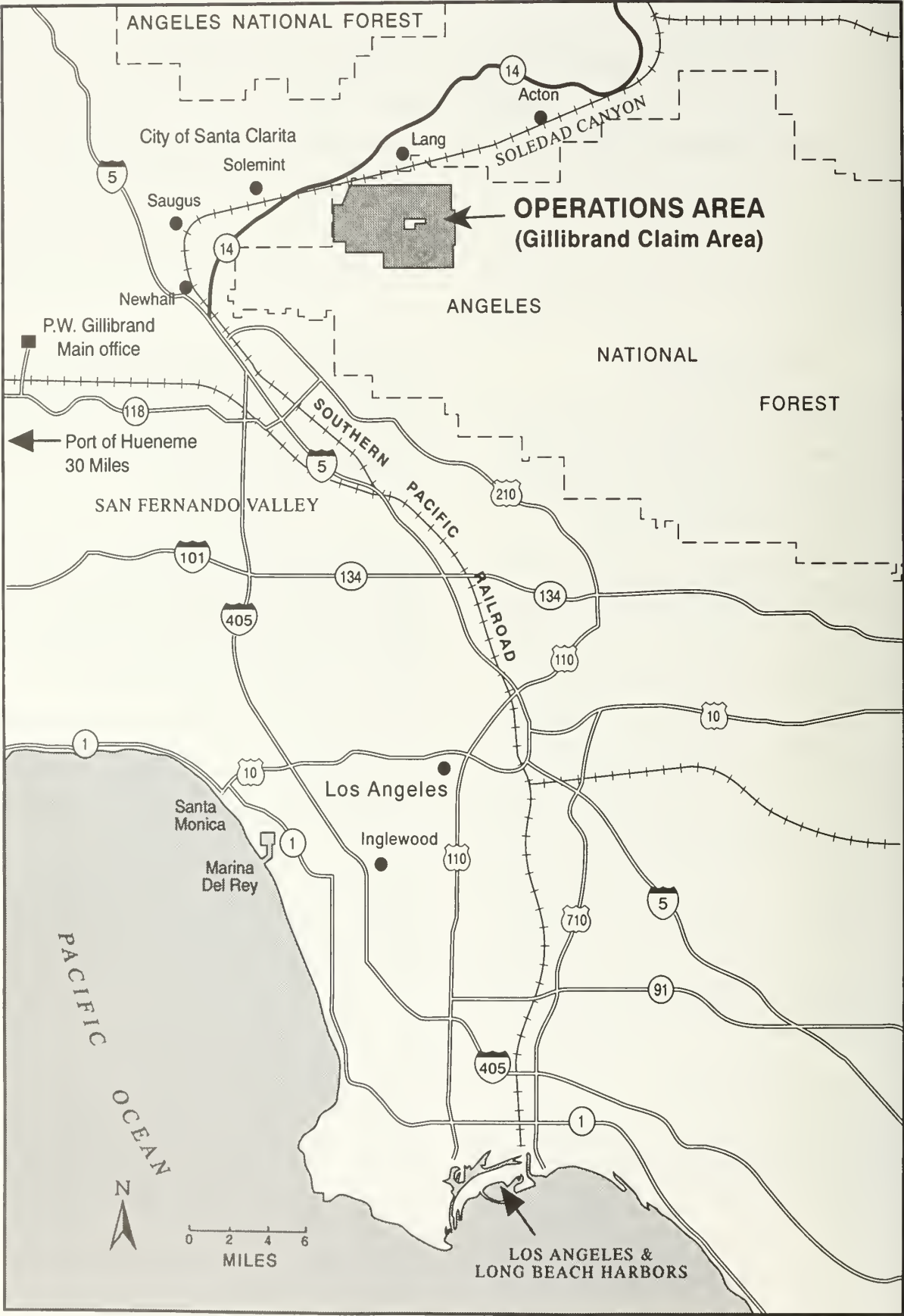


Figure 1. Location Map.

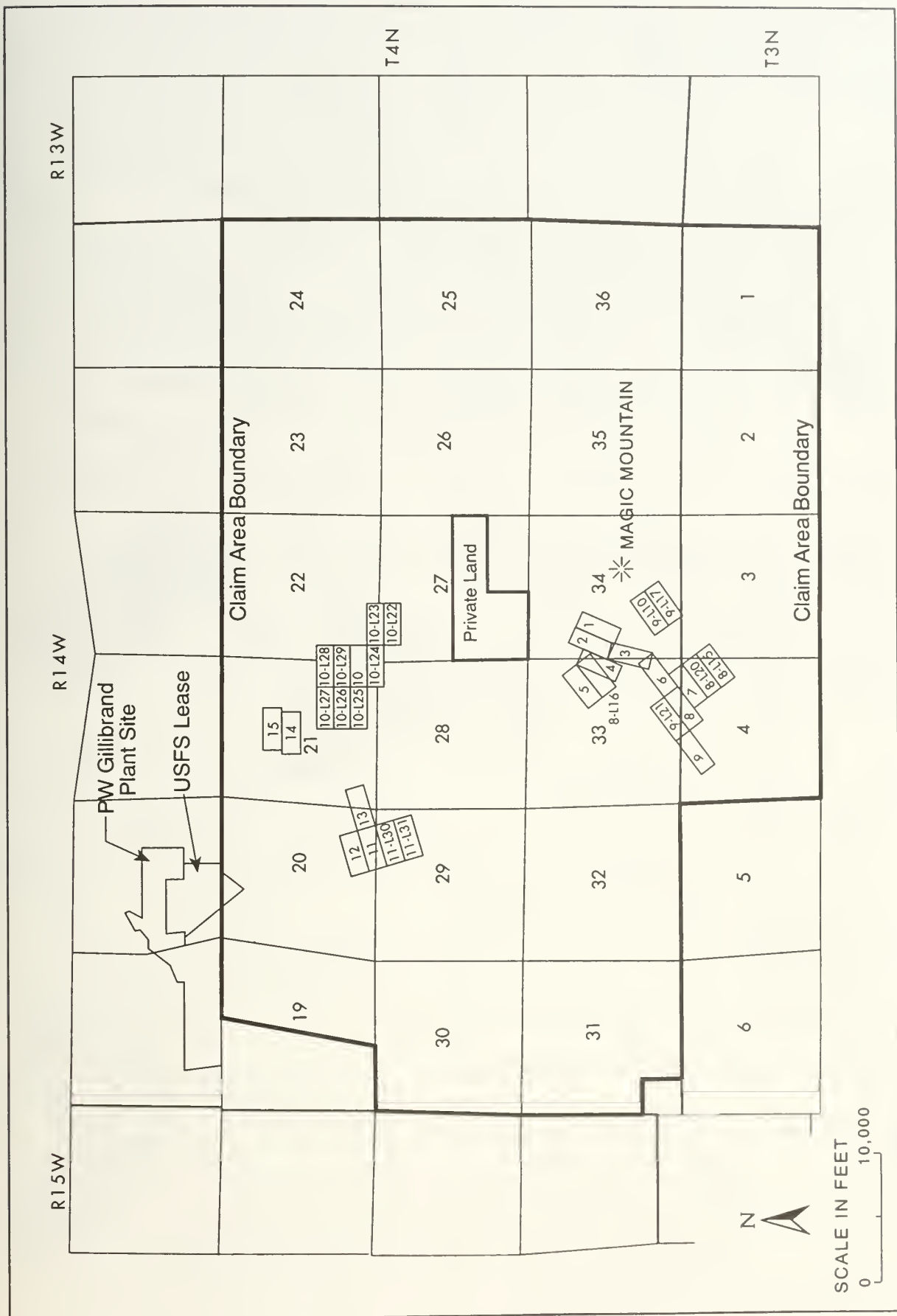


Figure 2. Gillibrand Mining claim boundary, San Gabriel Mountains, Southern California.



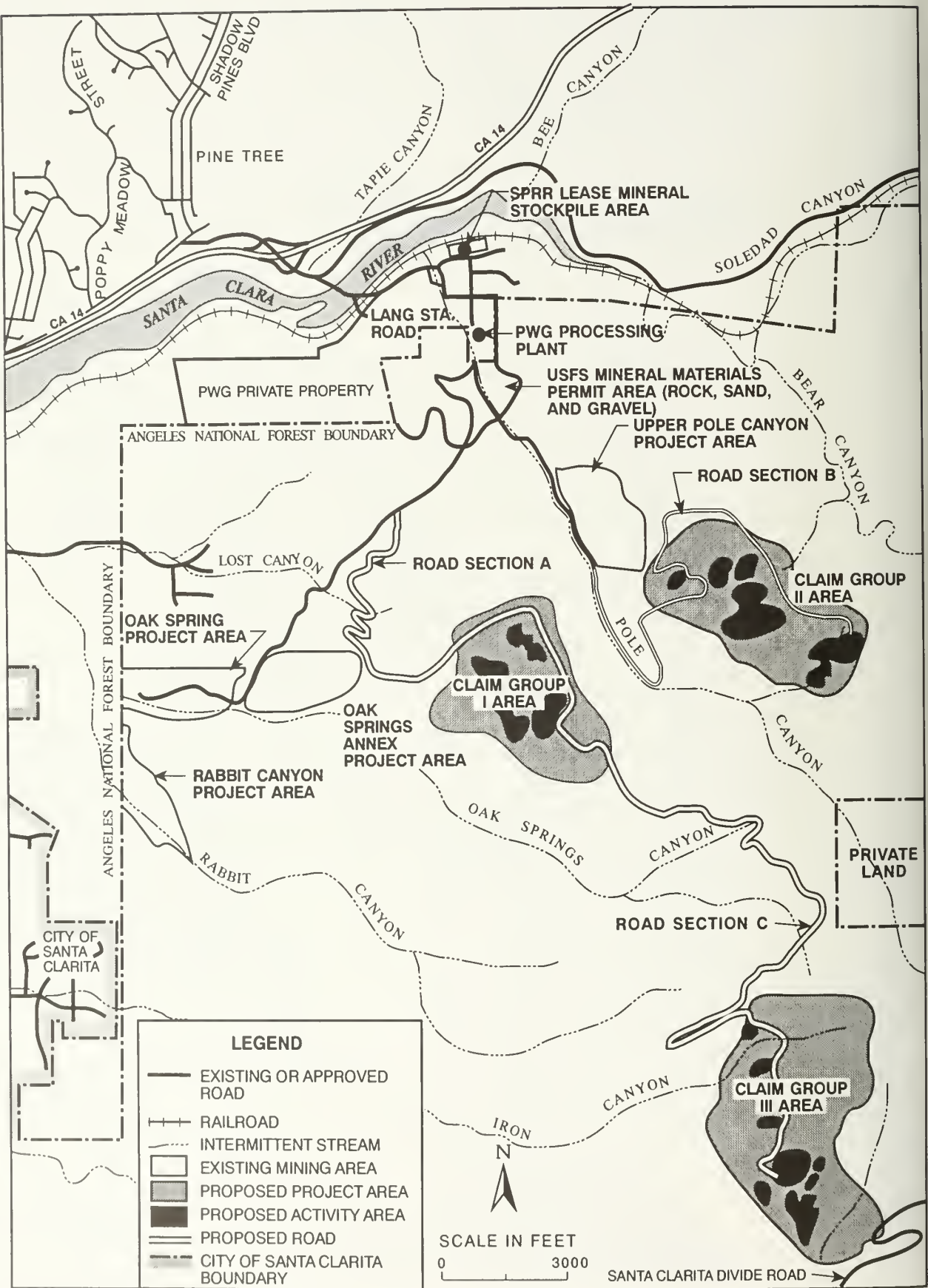


Figure 3. Location of target hard rock mining areas.

The P.W. Gillibrand Co. has been quarrying sand and gravel aggregates from both the Complex itself and its gravel outwash since 1967 (Nichols and Fife, 1970). In Pole Canyon (Figure 3) the company mines ferros from a U.S. Forest Service Mineral Materials Management Area. Drilling and blasting is required for excavating the gabbro which is sold as rip rap or is crushed and used as asphaltic concrete aggregates and crushed aggregate base materials.

A few miles to the west of the Pole Canyon quarry, are Oak Springs Canyon and Rabbit Canyon alluvial deposits (Figure 3). These placer claims have been mined since 1984 and have provided the feedstock to test the performance of the primary gravity concentration plant. By-product sand and gravels are marketed as Portland cement concrete aggregates.

### Mining

The P.W. Gillibrand Company has been mining aggregates in the western San Gabriel Mountains since 1967. There are three distinct types of orebodies from which heavy minerals can be extracted: (1) placer deposits in the Oak Springs Canyon and Rabbit Canyon (total heavy mineral concentrates range from 15 to 22%); (2) massive ilmenite-magnetite-apatite units typically associated with ferrogabbros and pyroxenites. These rocks contain as much as 35%  $\text{TiO}_2$  (up to 85% heavy minerals); and (3) as a by-product accessory concentrate recovered from mining the gabbro for aggregates. The ferros contain 14 to 15% heavy minerals.

Traditional open pit mining methods are used. The placer deposits are mined in 25 foot benches using a front-end loader to excavate the bench and haul the mine truck. Overburden is minimal consisting only of topsoil removal. There may be 3 or 4 mineable lifts in the placer deposits before non-heavy mineral bearing strata are encountered.

The hard rock quarries are developed in a series of benches and ramps. The benches are drilled and blasted. Wheeled front-end loaders place the ore in dump trucks to be transported to the processing plant.

### Regional

The San Gabriel Mountains form the major central part of the Transverse Range Province described by Carter (1980). The province extends from the Channel Islands eastward approximately 300 miles to the Eagle Mountains in the Mojave Desert. Its northern boundary is defined by the strike of the San Andreas fault and the Mojave Desert. The San Gabriel and related faults form the southern margin with the coastal lowlands of the Los Angeles basin.

The province obtained its name because of the east-trending nature of the range which is "transverse" to the prevailing northwest trends of the features of the Coast Range Province to the northwest and the Peninsula Range Province to the southeast.

### Local

The geology of the San Gabriel Anorthosite Complex has been described by Oakeshott (1958), Silver and others (1963) and Carter (1980, 1982). The Complex comprises a well fractionated anorthosite-syenite-gabbro assemblage of rocks (see Figure 4). The anorthosite massif is oval in outcrop about 19 miles long by 7 miles wide with a east-west trend, clearly intrusive into the older Mendenhall Gneiss and zoned from norite at the margins to anorthosite in the core. The age of the anorthosite from U-pb in zircon has been determined to be 1220 m.y. (Silver and others, 1963).

Within the complex, the gabbroic and pyroxenitic rocks have intruded into anorthosites. The rocks of the complex have been intruded by diabase, diorite, quartz diorite, granodiorite, syenite, granite and aplite. Late stage hydrothermal activity has altered the primary mineral assemblage in rock of the Complex to amphibolite, biotite and chlorite. Much of the pyroxenites have been extensively altered to amphibolites comprising riebeckite-richterite and cummingtonite. Ilmenite-apatite-magnetite rich gabbroic and pyroxenitic zones are present and represent the prime target for the exploitation of the heavy minerals.

### Mineralization

The main ore minerals of economic interest on the Gillibrand claims are ilmenite, magnetite and apatite. Ilmenite-magnetite-apatite rocks are commonly associated with Precambrian anorthosite massifs. In the San Gabriel Anorthosite Complex, these three minerals are abundant ubiquitous constituents in several mappable lithologic units, such as, the ferrogabbro and ferrosyenite. These three minerals also occur as nearly pure ilmenite-magnetite-apatite rock (IMA Rock). IMA generally occurs as small discontinuous lenticular or podiform bodies within the main rock units. Some IMA bodies exist in mineable quantities and are the target of the Gillibrand explorations plan.

Carter (1980) and Hastings (1990) have shown that the IMA rich gabbroic rocks of the Complex are cumulate rocks produced by crystallization and mineral sedimentation of late stage titanium, phosphorous and iron enriched magma. Petrologic evidence indicates that the ilmenite, magnetite and apatite crystallized in and with

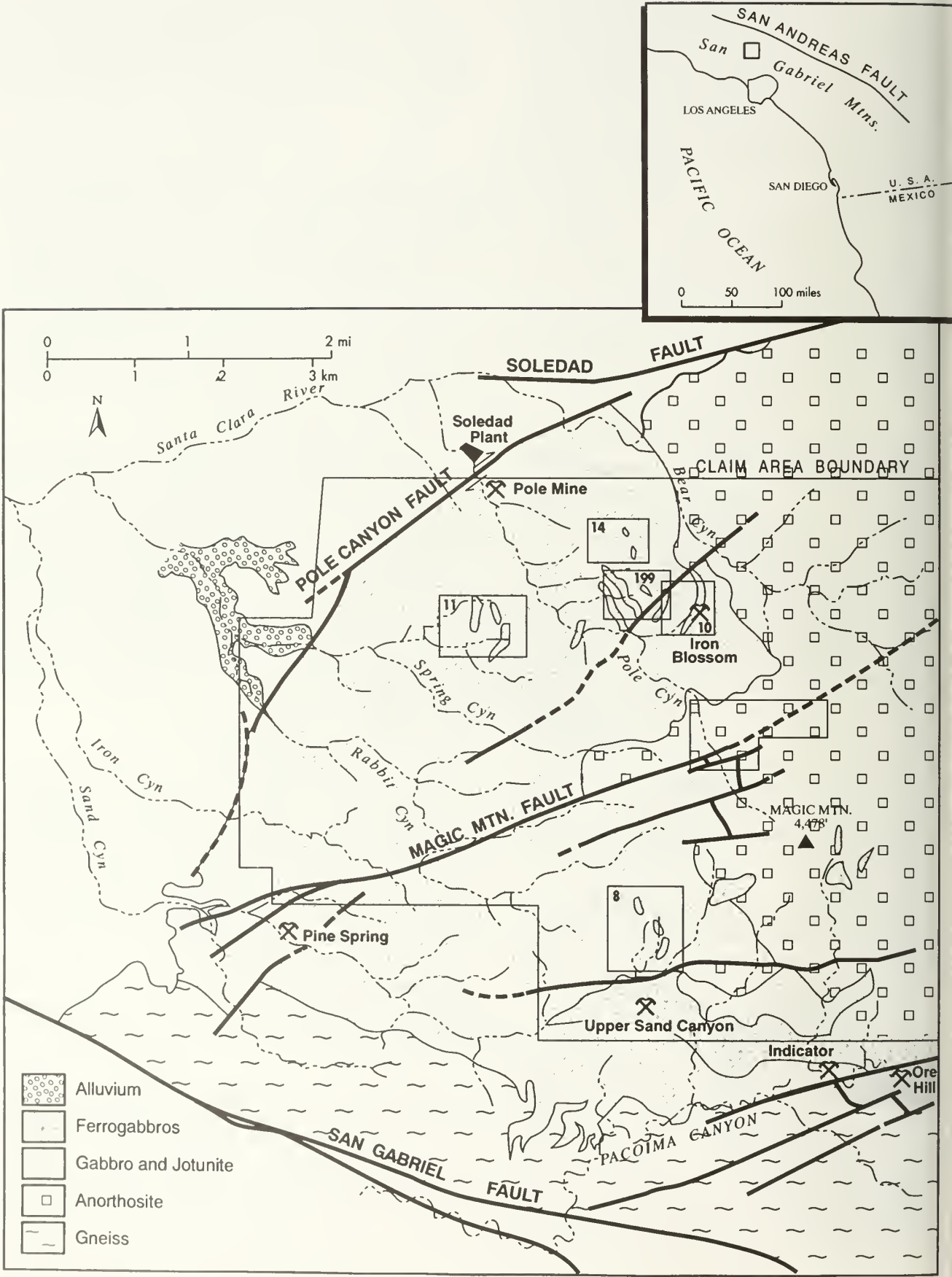


Figure 4. Simplified Geologic Map of the western San Gabriel Mountains, Los Angeles County, California.



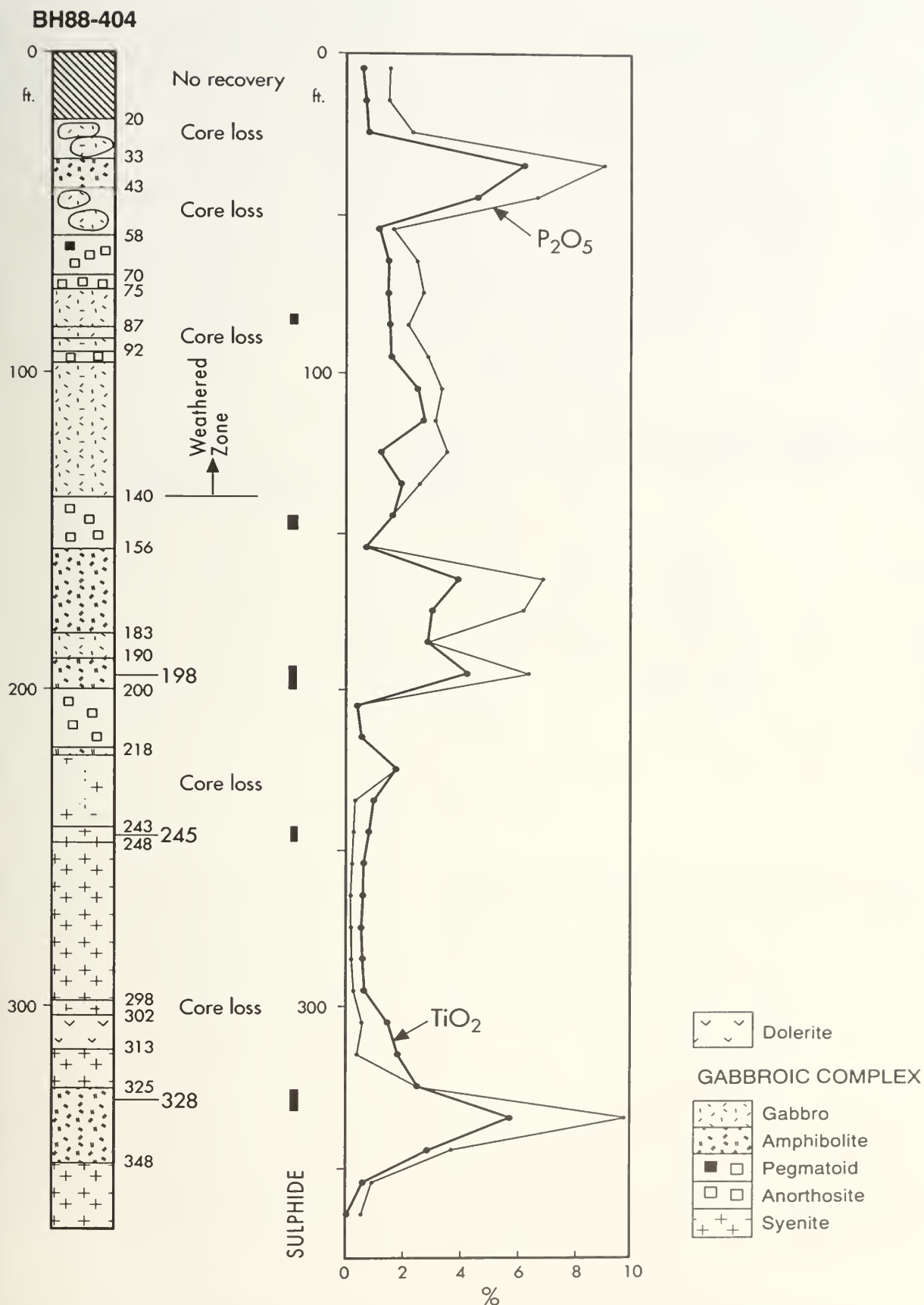


Figure 5. Log of Borehole 88-404 drilled in Claim Group III (see Figure 3 for location) showing Petrography and  $P_2O_5$  and  $TiO_2$  results of whole-rock geochemistry on regular 10-foot sections of core.

Table 1. Whole Rock Geochemistry.

MAJOR ELEMENTS (percent)				
Sample	IMA	Anorthosite	Gabbro	Syenite
SiO <sub>2</sub>	20.0	58.5	46.9	57.8
TiO <sub>2</sub>	13.3	0.1	3.4	0.6
Al <sub>2</sub> O <sub>3</sub>	4.7	26.0	14.0	16.2
FeO	32.4	0.5	14.9	6.6
MnO	0.4	Nil	0.3	0.2
MgO	5.8	0.1	4.2	0.5
CaO	12.3	7.5	8.4	3.5
Na <sub>2</sub> O	0.4	6.4	3.1	5.0
K <sub>2</sub> O	0.1	0.9	0.8	5.0
P <sub>2</sub> O <sub>5</sub>	7.4	Nil	2.3	0.3
BaO	0.2	0.1	0.1	0.3
TOTAL	97.0	100.1	98.4	96.0
TRACE ELEMENTS (percent)				
V	241	<10	193	12
Cr	52	35	31	68
Co	80	<10	39	10
Cu	14	<10	41	<10
Zn	419	<10	169	58
Mo	<5	<10	<5	<10
Sr	186	989	819	242
U	<10	20	24	<10
Th	42	23	41	22
Nb	23	<10	23	<10
Zr	90	<10	88	1330
Y	106	<10	46	14

Table 2. Mineral Concentrates.

MAJOR ELEMENTS (percent)				
Sample	ilmenite	Magnetite	Apatite	Zircon
SiO <sub>2</sub>	2.7	3.8	4.9	28.4
TiO <sub>2</sub>	51.0	3.9	Nil	0.1
Al <sub>2</sub> O <sub>3</sub>	0.8	1.3	1.4	0.9
FeO	38.1	-	-	-
Fe <sub>2</sub> O <sub>3</sub>	4.4	90.6	0.3	0.5
MnO	1.4	0.1	0.1	0.1
MgO	0.6	0.9	0.2	< .1
CaO	0.5	0.4	47.7	0.2
Na <sub>2</sub> O	Nil	0.1	0.6	0.5
K <sub>2</sub> O	0.1	0.1	0.1	<.1
P <sub>2</sub> O <sub>5</sub>	0.3	0.2	38.0	0.2
BaO	0.1	0.1	0.1	0.2
ZrO <sub>2</sub> + HfO <sub>2</sub>	-	-	-	67.8
TOTAL	100.0	101.5	93.4	98.9
TRACE ELEMENTS (ppm)				
V	390	2612	34	100
Cr	14	98	74	77
Co	60	93	<10	-
Cu	<5	<5	<10	900
Zn	211	131	<10	95
Mo	<5	<5	30	-
Sr	50	26	986	258
U	<10	<10	54	227
Th	<10	<10	63	252
Nb	250	<10	10	300
Zr	270	50	2000	-
Y	<10	<10	847	1041

the mafic silicates that sedimented out on the floor of a magma overlying the anorthosite core. The origin of the IMA enriched magmas from which these rocks crystallized is a result of an immiscible oxide-apatite phase which separated from magmas that underwent strong differentiation to form the IMA Rock. Figure 5 is a typical log of a borehole showing the petrology and whole rock geochemistry (Table 1) of the cumulate layers.

### Mineral Processing

The heavy mineral content, liberation size and grindability varies with rock type and area. Laboratory tests performed by CARPCO, Jacksonville, Florida; ERIEZ MAGNETICS, Erie, Pennsylvania; TICON, Keystone Heights, Florida, P.W. GILLIBRAND CO. and many others indicate the valuable minerals liberated by crushing the rock are readily amenable to standard ore dressing tech-

niques, such as, gravity, magnetic and electrostatic separation with good recovery and product quality. Tab 2 shows the chemistries of the heavy minerals extracted from the ore. Petrographic studies of rock from the target areas show that the magnetite and ilmenite grains range from 1.25M (14-16 mesh) down to 0.1mm (140-200 mesh). The apatite and zircon grains range from 0.7mm (25-30 mesh) down to 0.05mm (270-325 mesh).

Since 1984, heavy mineral concentrates have been produced from the alluvium in Oak Springs Canyon and Rabbit Canyon. A simplified flowsheet of the heavy mineral plant is shown in Figure 6. Coarse ilmenite and magnetite are currently being separated as saleable products. The remaining concentrates (i.e., fine ilmenite, apatite and zircon) are stockpiled for future processing.

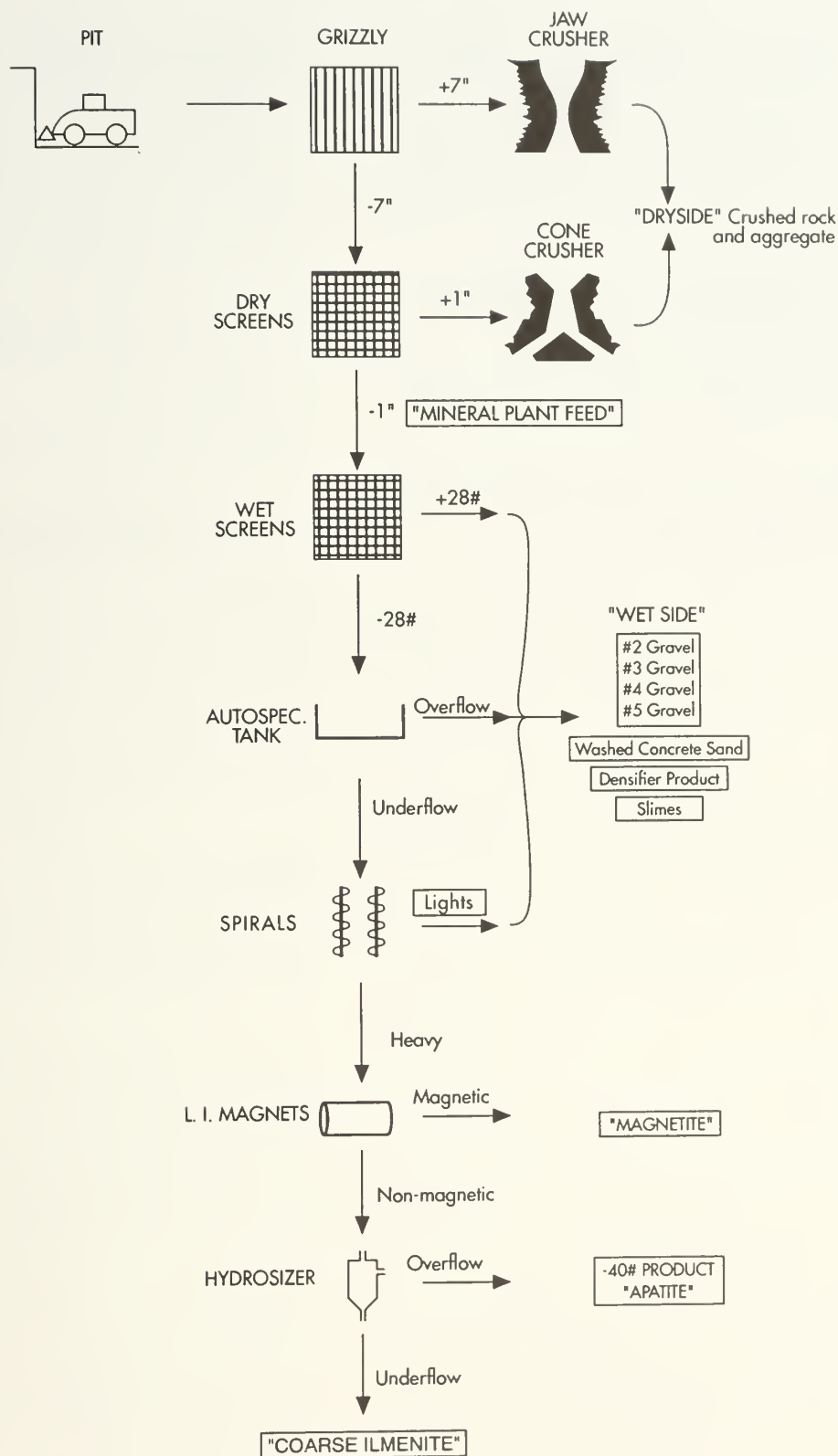


Figure 6. Simplified flowsheet of P.W. Gillibrand Co. Heavy Mineral Plant, Soledad Canyon, California.



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# Diatomaceous Earth Operation Grefco, Inc., Lompoc, California\*

by  
David Jenkins<sup>1</sup>

## INTRODUCTION

Grefco Inc. operates two diatomite mines in the western Santa Ynez Mountains. The larger of the two mines, the Palos Colorados Mine, is located approximately seven miles southeast of Lompoc. The Miguelito Mine is located about two miles south of Lompoc on the west side of the Miguelito Canyon. Diatomite from the Palos Colorados and Miguelito mines is trucked to the Grefco plant at Lompoc for processing (Figure 1).

## HISTORY

Grefco, Inc. evolved from the originating Dicalite Company which in 1929 began operations at the Walteria plant in the Palos Verdes Hills south of Los Angeles. In 1942 Dicalite leased the Palos Colorados mine at Lompoc. In 1944 the Dicalite Company was purchased by Great Lakes Carbon Corporation.

Diatomite from Lompoc was shipped to the Walteria plant for processing until 1952 when the Lompoc plant was built. Meanwhile, in 1951 the rights to the Miguelito mine had been acquired assuring adequate reserves for the future. In 1958 the Walteria plant was shut down, and the plant was dismantled and re-erected at Lompoc. This plant established a second processing unit and virtually doubled Lompoc's production.

In 1966 Great Lakes Carbon Corporation sold controlling interest in the company to General Refractories Corporation. Grefco, a wholly owned subsidiary of General Refractories, currently operates the Lompoc operations along with several other deposits in the United States.

## GEOLOGIC SETTING

About 2,000 feet of stratigraphic section is exposed or inferred at the Palos Colorados Mine. The lower portion of the section is represented by the "upper" Monterey Formation (Late Miocene) which is characterized by alternating beds of diatomite, siltstone, argillaceous diatomite, silty diatomite, volcanic ash, and interbedded cherty sediments.

Lying conformably on top of the Monterey Formation is the Sisquoc Formation. The Sisquoc is distinguished from the Monterey by the absence of interbedded opaline and cherty shales (Dibblee, 1950; 1982). Except for the lack of cherts, the Sisquoc is not significantly different from the Monterey. Figure 2 presents a condensed stratigraphic column of the Palos Colorados Mine. Representative columns of the Sisquoc (Column 1) are also illustrated at an enlarged scale.

The diatomite of the Palos Colorados Mine is located in a large east-west basin which is folded into several anticlines and synclines (Figure 3). The anticlines and synclines plunge to the west, consequently the younger Sisquoc beds are found in the western portion of the mine. Sections A and B are both north-south sections with section A being east of section B.

At the Miguelito Mine only "upper" Monterey beds are present. Figure 4 illustrates a typical stratigraphic column from this mine. The beds at this mine formed in a similar basin and at about the same time as the Monterey beds at the Palos Colorado Mine. For the most part, the beds at this quarry are folded into east-west anticlines and

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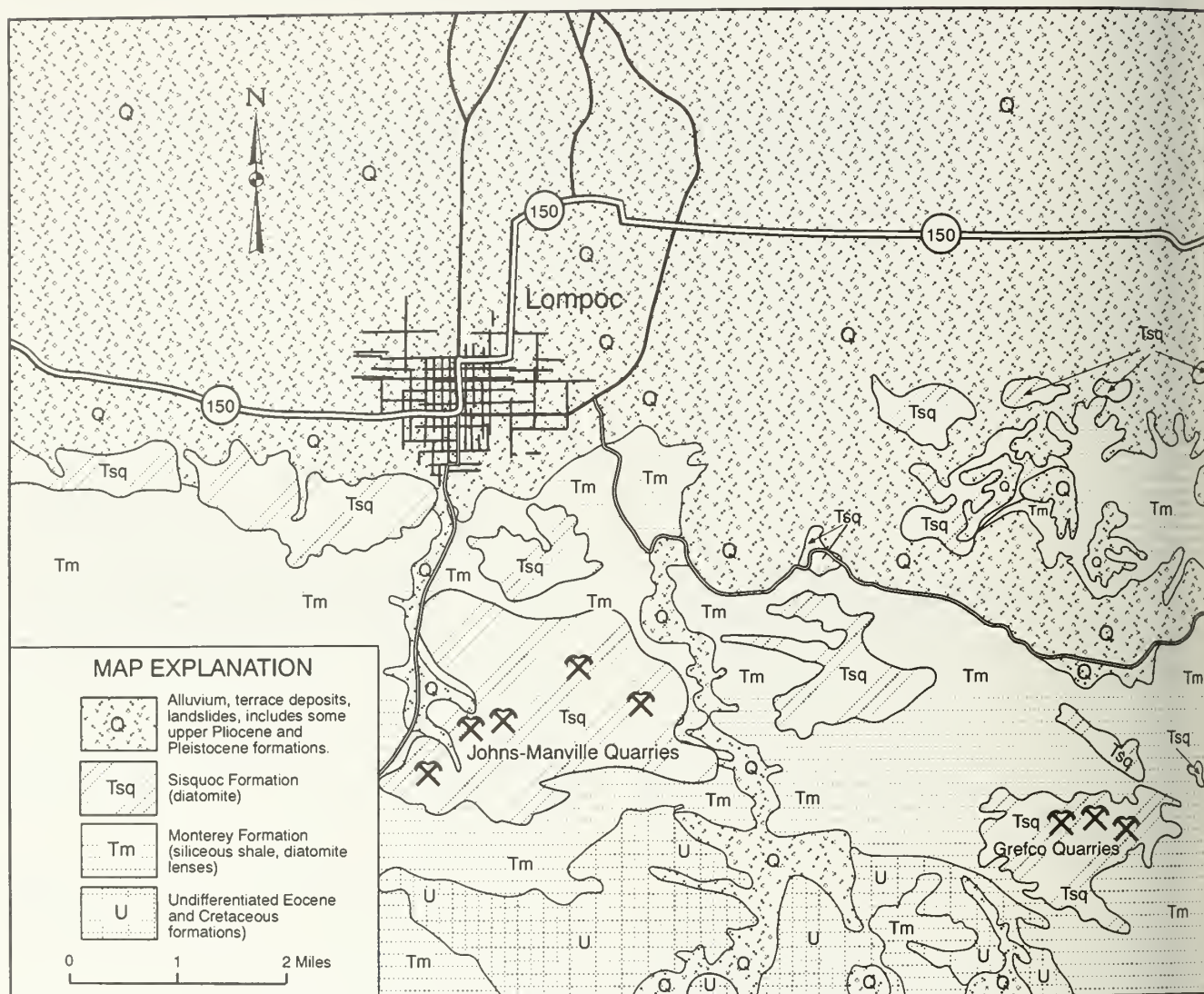


Figure 1. Location map. Geology taken from Plate 1, Bulletin 150, California Division of Mines and Geology

synclines. At the western end of the quarry the beds rise sharply terminating the deposit.

Economic beds of diatomite range from a few feet to tens of feet in thickness. The beds may be laminated or massive and the color of the diatomite varies from white to cream and occasionally light brown. The color is greatly influenced by moisture; diatomite that is white when dry may become light brown when wet.

## MINING

Mining at the Grefco quarries is done by open pit methods, as is all diatomite mining in the United States. Grefco, Inc. uses two mining systems at the Lompoc quarries. The system selected is determined by strata configuration: 1) ripping by dozer and lifting and hauling by scraper on wide or flat-lying beds where waste disposal

areas are adjacent to the quarry area and "crude" ore stockpiled on level surfaces for later hauling to the plant. 2) Front-end loaders are used on thin and/or steeply dipping strata. "Crude" is stockpiled adjacent to the working face and the waste is removed to the edge of the working area for subsequent scraper removal.

"Crude" is transported from the mines to the plant by bottom dump trucks. The haul distances range from seven to ten miles.

## Processing

"Crude" trucked from the quarries is separated by quality into ten to fifteen stockpiles. Desired "crudes" are blended from the various stockpiles and fed into a "crude" storage bin. Blending "crudes" makes it possible to produce many different products specifically suited to customer needs.



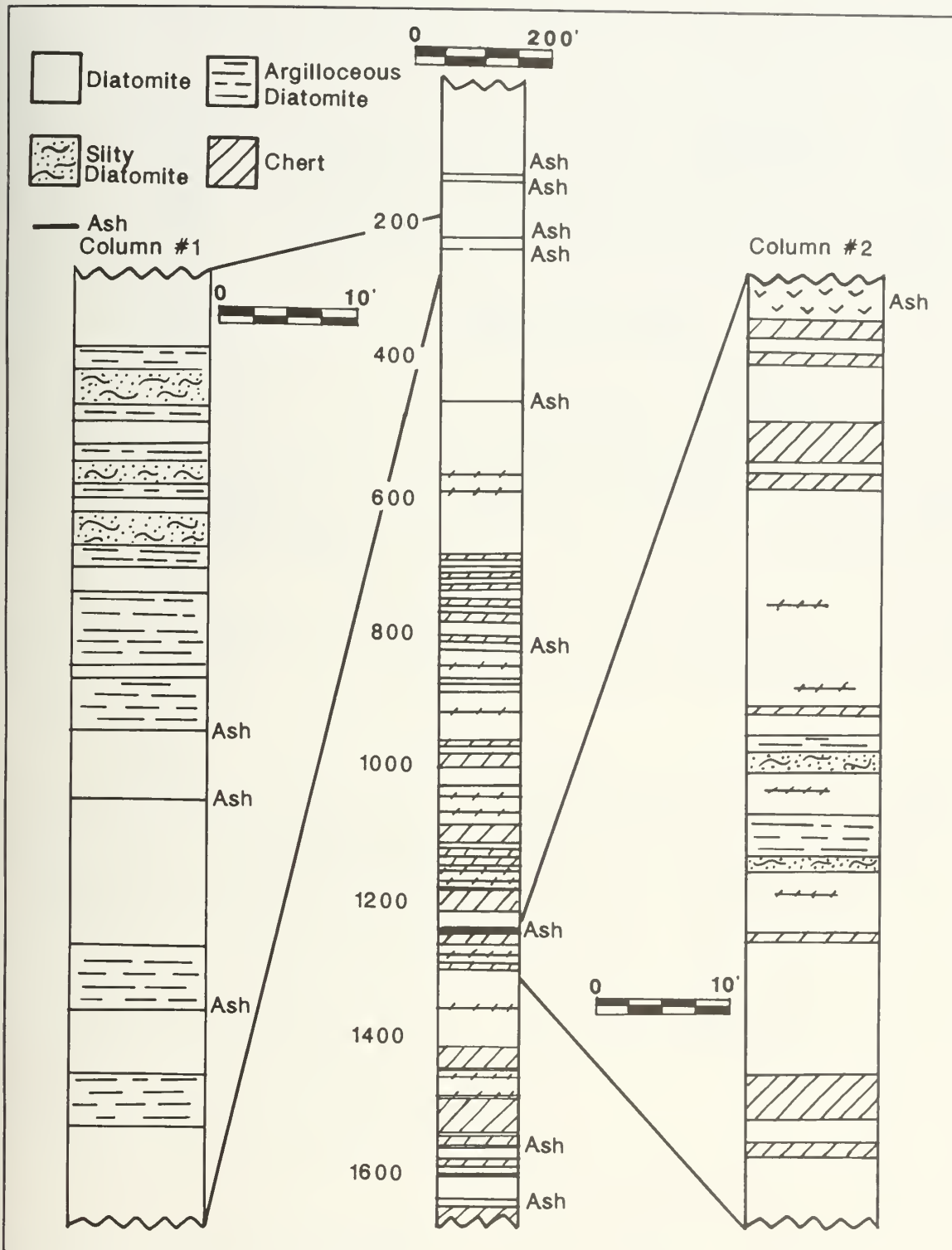


Figure 2. Stratigraphy of the Palos Colorados Mine.

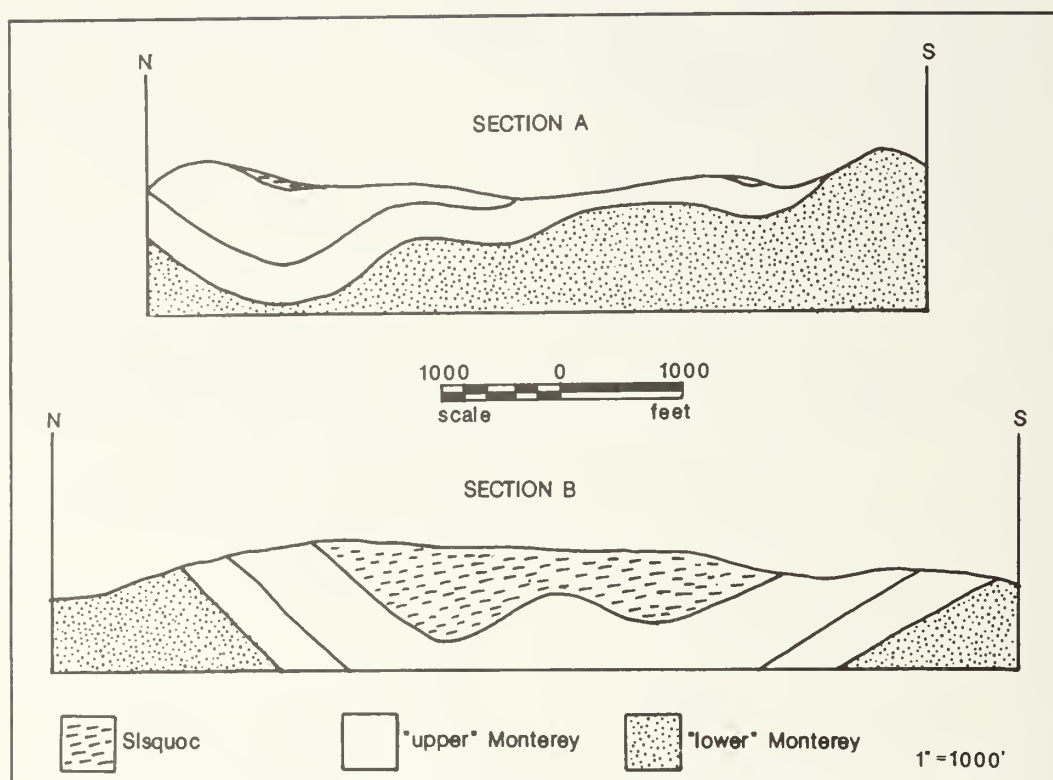


Figure 3. North-south cross sections of the Palos Colorados Mine.

Processing consists of two phases: the wet end phase and the finish end phase. The wet end phase includes flash drying, addition of a fluxing agent for white products, trapping impurities and classifying. The material then enters the finish end where additional trapping and classifying is done. Finally the product passes into one of the several bins for packing in bags or for bulk loading.

Two basic types of products are made at the Lompoc plant: calcined and flux-calcined. Calcined and flux-calcined products are commonly referred to as pink and white products due to their color. Flux-calcined products account for about 70% of the plant's production.

### Quality Control

Due to specialized uses of diatomite, many qualities need to be controlled to meet rigid product specifications. Prior to any mining, areas are drill samples. Waste rock is removed and strata to be mined are sampled. They are sampled again after they are put into stockpiles. At this point, the stockpiles are coded as to their quality and are later hauled to the plant as required. Stockpiles at the plant are continuously sampled and tested to monitor plant feed. Samples are frequently obtained at various stages in the processing and also at the final product stage. A final quality assurance check is made on all material prior to bagging or bulk loading.

### Uses

The widest use of processed diatomite is as a filter in such applications as in the beer, wine, sugar, and industries. It is also widely used to filter water. Depending upon the specific media being filtered and the flow rate desired, the products are customized into grades calcining alone or by adding flux--usually soda ash.

Another important use of diatomite is as a fill material, both "functional" and "nonfunctional." "Functional" alludes to the inherent properties of the diatomite such as abrasiveness, absorption, or insulating qualities. "Nonfunctional" or mineral filler uses are for more bulk as extenders for more expensive ingredients. These uses include use in paint, paper, asphalt products, and plastic.

### RECLAMATION AND ENVIRONMENT

Mining diatomite requires the removal of large amounts of overburden material. Generally, hills are mined and canyons are filled. As mining approaches its final stages, considerations are given to the final topography. Efforts are made to leave stable slopes and flat gentle grades. Overburden dumps are built in successive layers to assure good compaction and stable slopes.

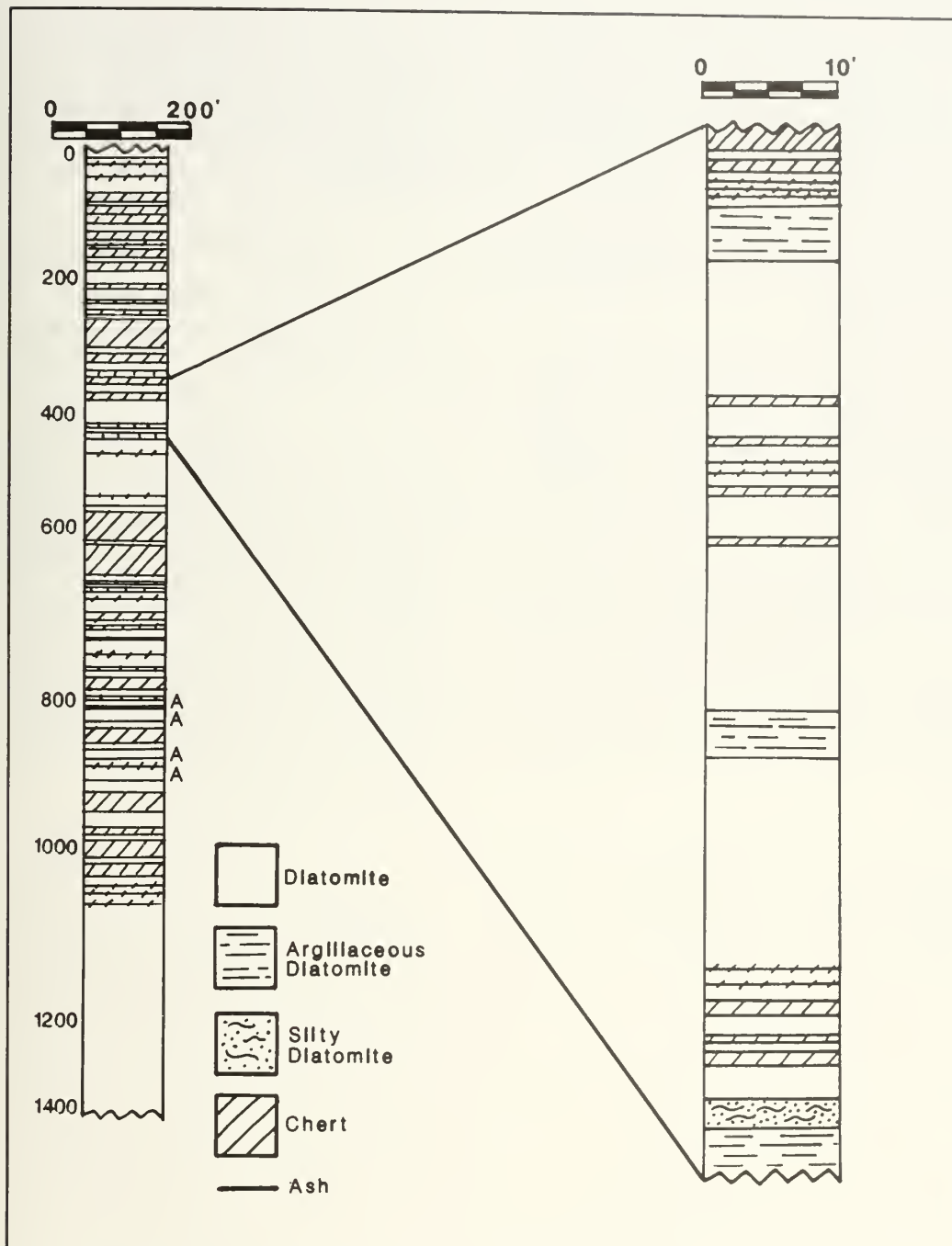


Figure 4. Stratigraphy of the Miguelito Mine.



Revegetation in the past has been all natural and quite successful. In more recent years a more active role in revegetation has been undertaken. Areas that have been permanently abandoned are covered with topsoil. These areas are then planted with various grasses. The goal is to create flat grassland for cattle grazing.

In addition, well over 1,000 trees are planted every year. Most of the trees planted in past years were pines or other conifers. Considerable success have resulted from recently planted oak trees.

Dust is controlled in the quarries by water trucks and water wagons. This requires constant effort but it keeps dust under control. Permanent roads are paved or treated to further reduce dust. Trucks hauling crude to the plant are required to wash down before leaving the property. Other trucks spray water to prevent blowing dust along the highways.

Rain run-off in the quarries is controlled in many ways. Abandoned areas are deep ripped and covered with soil to promote water retention. Where rain run-off occurs, slopes are engineered to reduce erosion. As a final check, all run-off is collected in siltation ponds to collect any debris or suspended material. Rainfall run-off from Grefco quarries is typically clearer than from surrounding unmined properties.

In many respects the quarry properties are now more productive than before mining. Much more of the land now being utilized by cattle due to improved access and water development. Wildlife has also increased its presence in the quarries and has especially benefited from the development of water supplies and the new growth resulting from reclamation.

## ACKNOWLEDGMENTS

I wish to express my appreciation to all those people at Grefco who made this paper possible. Special thanks due Joe Horton for his advice and comments. Paul Morton and Donald L. Fife reviewed the manuscript.

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# The Geology and Economic Development of Searles Lake

by  
Gail Moulton<sup>1</sup> and Ken Santini<sup>2</sup>

## ABSTRACT

Searles Valley is located approximately 125 miles northeast of Los Angeles in the Basin and Range Province. Occupying the lowest part of the valley is Searles Dry Lake Playa, which is about 9 miles long and 7 miles wide. Three major subsurface evaporite horizons have been identified and are termed from bottom to top, the Mixed Layer, Lower Salt and Upper Salt. The evaporite beds were formed by desiccation of runoff from the eastern Sierra Nevada during Quaternary time. The saline beds are generally brine saturated with the important ions being sodium, potassium, carbonate, bicarbonate, sulfate, chloride and borate. These ions are present in the brines in various concentrations and have combined to form the minerals halite, hanksite, trona, nahcolite, burkeite, borax, thenardite, sulfohalite, glaserite and others. North American Chemical Company selectively pumps the interstitial brines to feed their chemical plants located on the western edge of Searles Lake. Minerals have been mined since 1873, beginning with borax and trona scraped from the surface. Brine processing began in 1914 with potassium chloride and borax recovery. Expansions have added sodium sulfate and soda ash to the product mix. Currently, dredging of trona ore is also taking place.

## INTRODUCTION

Searles Valley, approximately 125 miles northeast of Los Angeles, is near the southwest corner of the Basin and Range Province and just north of the Mojave Desert. Occupying the lowest part of the valley is Searles Dry Lake Playa, which is approximately 9 miles long (north to south) and 7 miles wide (east to west). See Figure 1. The playa covers about 40 square miles at an elevation ranging from 1614 to 1624 feet above sea level. Mud forms much of the surface, although nearly pure halite crops out over an area of approximately 12 square miles in the center. See Figure 2.

To the west and northwest of Searles Valley is the northern half of the Argus Range. The highest elevation in the Searles Valley area is Argus Peak with a summit of about 6562 feet above sea level. On the southwest are the Singler Hills, the El Paso Mountains and the Lava Mountains. Also located on the southwest part of Searles Valley is the Pinnacles National Scenic Area. The Pinnacles are a unique geologic feature composed of vertical spires up to 140 feet in height. They occur in what is an arm-like bay on the southwest side of the former lake, and were formed by tufa precipitating around the

orifices of springs. To the southeast are the Granite Mountains. Well developed, coalescing alluvial fans extend into the valley from the Slate Range to the east. The fans in the Argus Range are not as well developed.

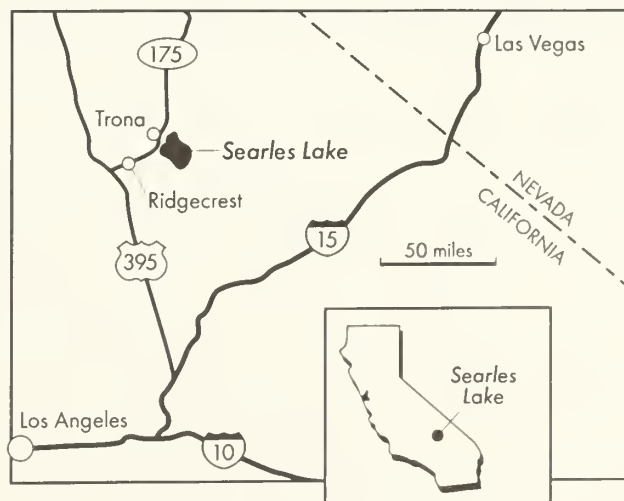


Figure 1. Location of Searles Lake, CA.

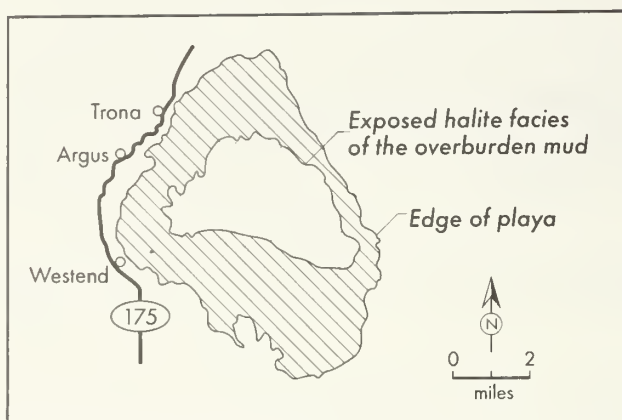


Figure 2. Searles Dry Lake Playa.

## GEOLOGY

Searles Valley is a closed structural basin filled with alluvium and non-marine evaporites. The thickness of the fill ranges from zero at the periphery to over 3,000 feet in the deepest portions of the basin. A core hole (KM-3), drilled in 1968, intersected basement rock at a depth of 3,003 feet. The bedrock found is quartz monzonite, which is also the major rock type of the Argus and northern Slate Ranges. In Searles Lake, brine-bearing evaporite horizons alternate with mud beds. See Figure 3. Evaporite horizons were formed during periods of high evaporation and low rainfall. The resulting beds are generally thicker in the lake center, and thin toward and eventually pinch out at the edges of the lake. Mud beds were formed during full lake conditions, and in most cases, become thicker toward the edges, grading into coarse, clastic sediments at the base of the mountains.

The saline beds are generally brine saturated, white to pink in color, hard and very porous. The important ions are  $\text{Na}^+$  (sodium),  $\text{K}^+$  (potassium),  $\text{CO}_3^{2-}$  (carbon-

Table 1. Minerals associated with the saline horizons.

Borax	$\text{Na}_2\text{B}_4\text{O}_7 \cdot 10\text{H}_2\text{O}$
Burkeite	$2\text{Na}_2\text{SO}_4 \cdot \text{Na}_2\text{CO}_3$
Glaserite	$\text{K}_3\text{Na}(\text{SO}_4)_2$
Halite	$\text{NaCl}$
Hanksite	$9\text{Na}_2\text{SO}_4 \cdot 2\text{Na}_2\text{CO}_3 \cdot \text{KCl}$
Nahcolite	$\text{NaHCO}_3$
Northupite	$\text{Na}_2\text{CO}_3 \cdot \text{MgCO}_3 \cdot \text{NaCl}$
Sulfohalite	$2\text{Na}_2\text{SO}_4 \cdot \text{NaCl} \cdot \text{NaF}$
Teepleite	$\text{Na}_2\text{B}_2\text{O}_4 \cdot 2\text{NaCl} \cdot 4\text{H}_2\text{O}$
Thenardite	$\text{Na}_2\text{SO}_4$
Tincalconite	$\text{Na}_2\text{B}_4\text{O}_7 \cdot 5\text{H}_2\text{O}$
Trona	$\text{Na}_2\text{CO}_3 \cdot \text{NaHCO}_3 \cdot 2\text{H}_2\text{O}$

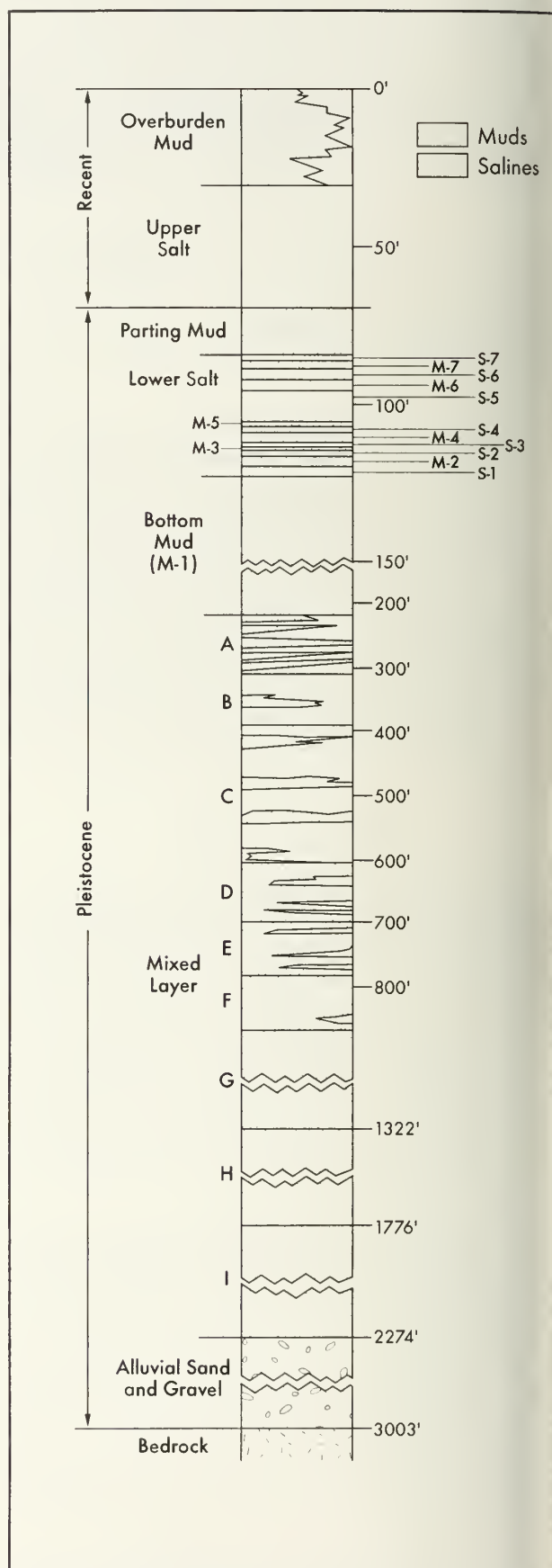


Figure 3. Stratigraphic column.



$\text{HCO}_3^-$  (bicarbonate),  $\text{SO}_4^{2-}$  (sulfate),  $\text{Cl}^-$  (chloride) and  $\text{B}_2\text{O}_7^{2-}$  (borate). These ions are present in the brines at various concentrations, and have combined to form the major evaporite minerals of halite, hanksite, trona, nahcolite, burkeite, borax, thenardite, sulfohalite and mirabilite. See Table 1.

The mud beds, in general, are dark green to brown, fine-grained, porous, and may have a distinct mercaptan (rotten eggs) odor. The important ions in the muds are  $\text{Ca}^{2+}$  (calcium),  $\text{Na}^+$  (sodium),  $\text{Mg}^{2+}$  (magnesium) and  $\text{CO}_3^{2-}$  (carbonate). These have precipitated as fine-grained aragonite and dolomite, in addition to fine and coarse-grained gaylussite and pirssonite. The surface mud bed (Overburden Mud) also contains halite, borax, hanksite, trona and thenardite locally.

### Mixed Layer

The Mixed Layer is a sequence of mud and evaporite beds overlying arkosic sand and gravel. See Figure 3. The oldest muds were estimated to be 3.2 million years old (Smith, 1979). Although the lateral and vertical extent of the Mixed Layer beds have not been fully explored, they are known to cover less area than younger, overlying surface evaporites. See Figure 4. The Mixed Layer has a complicated structure, including tight folds and faults, which are not found in the younger Bottom Mud.

The upper Mixed Layer is divided into several units based on differences in electrical conductivity and mineral composition, while the lower Mixed Layer is divided on the basis of mineral composition alone. There are a total of nine units present (A to I). Since the upper Mixed Layer evaporite horizons are predominantly trona and nahcolite, the resulting interstitial brines are high in sodium

carbonate and low in sodium chloride. Thus, these horizons are of value as a soda ash source. In contrast, the lower Mixed Layer evaporite horizons consist mostly of halite and thenardite, which makes them unsuitable as a soda ash source. When these latter two minerals dissolve, they prevent carbonate minerals from dissolving, resulting in a low sodium carbonate grade.

### Bottom Mud

The Bottom Mud is underlain by the Mixed Layer and overlain by the Lower Salt. This mud horizon covers a much larger areal extent than the saline beds above. It is about 100 feet or greater in thickness and forms a bowl-shaped structure with the thickest part near the lake center. The unit is composed of mud beds with abundant gaylussite and minor dolomite, calcite, halite, thenardite, mirabilite, trona and borax.

### Lower Salt

The Lower Salt is underlain by the Bottom Mud and overlain by the Parting Mud. Thickness ranges from approximately 40 feet in the lake center to zero at the edges. It is composed of seven evaporite beds separated by six mud beds. The evaporite beds are predominantly trona and halite, although borax, burkeite, nahcolite and northupite are also found.

The mud beds are composed of dark, clay-sized saline and clastic minerals, in addition to megascopic crystals of gaylussite, pirssonite, halite and borax.

Lateral changes from the lake center to the edges include (1) an increase in the carbonate content of the brine; (2) a decrease in halite content and (3) a thickening of the mud beds.

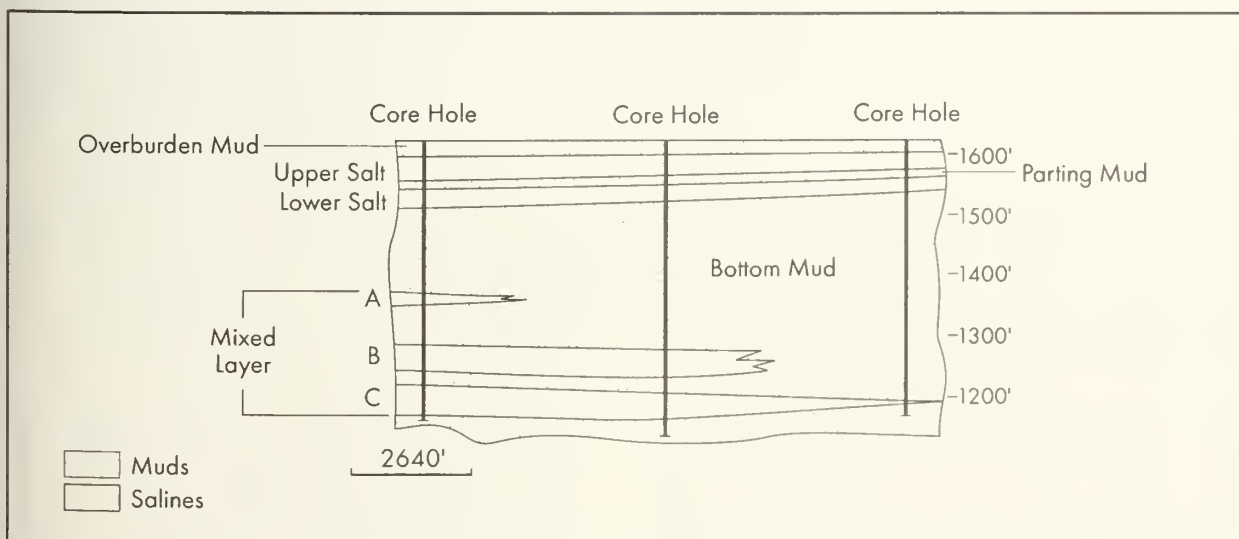


Figure 4. Geologic Cross section (looking north).

## Parting Mud

The Parting Mud is underlain by the Lower Salt and overlain by the Upper Salt in the central part of the lake. It is in contact with the Bottom Mud and Overburden Mud around the edges of the lake. The horizon is approximately 10 feet thick in the lake center and thickens to 26 feet or more toward the edges. On the periphery of the lake, this mud unit is difficult to distinguish from the Bottom and Overburden Muds.

The Parting Mud is composed of saline and clay-sized clastic minerals, as well as abundant megascopic pirssonite and gaylussite with minor amounts of borax, northupite, trona and hanksite. The content of soluble minerals may exceed 50 percent in some areas.

## Upper Salt

The Upper Salt is underlain by the Parting Mud and overlain by the Overburden Mud. It ranges in thickness from about 75 feet at the lake center to zero along the edges.

The unit can be divided into two members. The lower member extends to the outer edges of the lake and is composed mostly of beds of trona and halite. Thin beds of hanksite and borax, and minor amounts of burkeite and thenardite are also found. Similar to the Lower Salt, the halite content decreases toward the lake edges. The lower member of the Upper Salt is generally thin in the lake center and thickens toward the edges, before it pinches out. However, this is not true on the east side of the lake, where the bed thins abruptly. The upper member of the Upper Salt is thickest at the lake center, and thins toward the edges. It is composed of halite and hanksite with some trona beds, and minor amounts of borax and sulfohalite.

## Overburden Mud

The Overburden Mud is underlain by the Upper Salt. It is characterized by two facies. The central facies is approximately 23 feet thick and is composed of alternating saline and mud beds. Most of the salines are halite, however, locally beds of hanksite, trona, borax and thenardite are found. Pirssonite also occurs in this facies. Toward the edges of the lake, the halite facies grades into a dark brown to black pirssonite-bearing mud, which is up to 33 feet thick. This mud unit, in turn, grades into silt, sand and gravel.

## GEOLOGIC ENVIRONMENT AND HISTORY

Searles Valley contained a series of lakes for much of the last 3.2 million years. During pluvial periods of the Pleistocene, Searles Lake was the third in a chain of five lakes, which received water from Owens River. See Figures 5 and 6. Owens River received most of its water from the eastern slopes of the Sierra Nevada and transported it

to Owens Lake. Although, during some periods, Mono Lake and tributaries to that basin, also added their water to those of Owens River. When Owens Lake filled to a level about 200 feet above its present surface, it overflowed southward into China Lake. China Lake, in turn, overflowed eastward into Searles Valley to form Searles Lake. During its highest stages, Searles Lake stood at a level 640 feet above the present valley floor, and coalesced with China Lake to form one body of water. This large lake overflowed around the south end of the Sierra Range into Panamint Valley, where a lake 60 miles long and 930 feet deep was formed. Panamint Lake, in turn, spilled over Wingate Pass into Death Valley. However, Searles Lake was usually the last in the chain and, as a result, underwent extreme fluctuations in lake level. With the large combined drainage area of the connected lakes, small changes in regional precipitation drastically altered the quantity of water flowing into Searles Lake. When the lake was cut-off from upstream water, inflow was greatly reduced and evaporation quickly converted Searles into a small saline lake or salt playa. The periods when precipitation increased enough to restore inflow from upstream, the basin would fill, occasionally reaching overflow levels approximately 460 feet above the present surface.

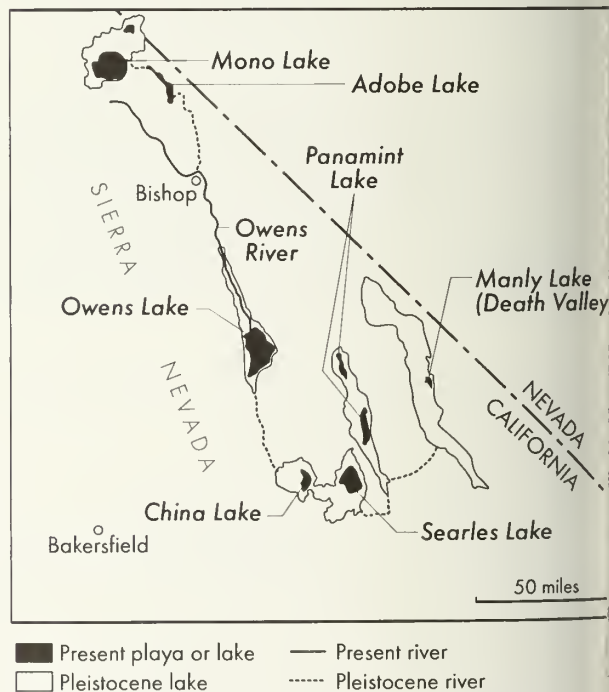


Figure 5. Pleistocene lakes of the Owens river system.

The large volume of components in the evaporite horizons of Searles Lake was introduced into the valley water. Many of the components are found in almost all waters draining from bedrock terrane, among them, calcium, sodium, potassium and magnesium. All natural

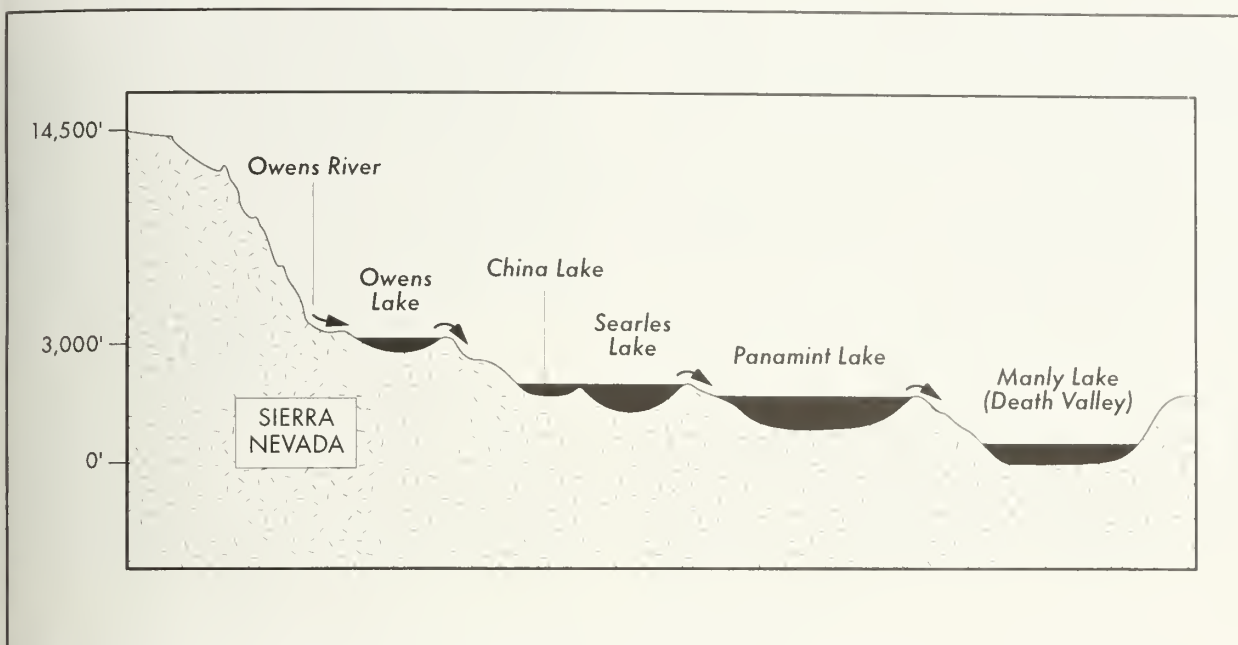


Figure 6. Chain of Pleistocene lakes, Owens river system.

ers also contain carbonate and bicarbonate contributed by the atmosphere. Smith (1976), estimated that about two-thirds of the sodium, chlorine and bromine were derived from atmospherically transported sea salts, and the solution of Cenozoic halite deposits in the drainage area. Approximately one-third of the sodium, chlorine and bromine came from thermal springs in the Long Valley area (south of Mono Lake). Most of the boron was derived from these thermal springs. In addition, some boron was contributed by the Coso thermal springs located southeast of Owens Lake. The erosion of Cenozoic igneous beds and gypsiferous sediments in the drainage area provided sulfate to Searles Lake.

The fine clastics in lake muds were also transported into Searles Valley by inflow waters. These sediments were mixed with showering chemical precipitates formed by calcium and magnesium ions, in predominantly runoff water, reacted with carbonate rich brackish water and brines trapped in Searles Valley.

## COMMERCIAL DEVELOPMENT

Commercial development of Searles Lake extends back to the efforts of John Searles, who recognized that borate crystals being recovered by Francis "Borax" Smith from Teels Marsh in Nevada, were similar to crystals he found on Searles Lake. The discovery prompted John and Denis Searles to stake mining claims on the north end of Searles Lake and build a small experimental plant about 10 miles south of the present town of Trona. In 1876, the Bernardino Borax Mining Company was formed with John Searles as president. The original land holdings had expanded to 3 square miles. A plant was constructed with a reported capacity of 100 tons per month of borax.

Water supplies were developed from mountain springs south of Trona and a mule-drawn freight line was established to San Pedro to ship the product. This company operated until 1898.

The first plant designed specifically to recover potash was the Hornsey plant. The process initially carbonated brine to remove  $\text{Na}_2\text{CO}_3$ . This was followed by evaporation to remove  $\text{NaCl}$ . The concentrated brine was cooled to recover a mixed crop of borax and  $\text{KCl}$ . The liquor was then evaporated further to remove  $\text{Na}_2\text{SO}_4$  and  $\text{NaCl}$ , which were discarded. The mother liquor was again carbonated to remove the rest of the carbonate. Then it was mixed with the end brine, from the recrystallization of the mixed borax and  $\text{KCl}$  crop, to crystallize a marketable murate of potash. The Hornsey plant was dismantled in 1914.

During the Hornsey experiments and after reorganization of the company in 1913 as the American Trona Corporation, company president, Baron De Ropp, retained Charles P. Grimwood to develop a potash process. His experiments led to the one-step Grimwood process involving high temperature evaporation of brine, followed by cooling and crystallization of potash. Potash mother liquor was recycled to the evaporator. Construction of the plant began on October 21, 1916 in San Pedro, but it operated only intermittently. Grimwood's connection was severed in May 1918, but process development continued under John Teeple, a consulting chemical engineer, and the plant technical staff. Initially, the borax content of the potash product was too high for agricultural use. However, H. W. Morse discovered that potash crystallizes rapidly, while borax remains supersaturated



in the mother liquor. This occurs long enough to efficiently separate the two products, thereby providing a satisfactory potash product. This improvement is still the basis for today's potash recovery process. In fact, the borax limit in potash product set by Morse and Teeple (0.5 percent) is the same limit in use today. As part of the quality improvement process for potash, a plant to recover purified borax was also installed. The first car of borax was shipped to the Corning Glass Works in May 1919.

The American Potash & Chemical Corporation was formed on June 4, 1926, to acquire the entire properties of the American Trona Company, which included the California Trona Company, the Trona Mercantile Company and the Trona Railroad Company. Remodeling and expansion of the plant, carried out under the new organization, were completed in 1927. During this remodeling, it remained in partial operation. The plant was further expanded in 1931 by addition of the soda products plant and No. 3 evaporator in 1937, followed by the carbonation plant in 1947. A further expansion was completed in 1962, with the addition of the No. 4 evaporator and the boric acid extraction plant, bringing the total plant capacity to 900,000 tons per year of primary production. American Potash & Chemical Corporation merged with Kerr-McGee Corporation on December 29, 1967. On December 1, 1990, North American Chemical Company acquired the entire Searles Valley Operation.

The second successful plant on Searles Lake, the Westend plant, was founded by "Borax" Smith. In 1918, he built a small plant, but it was plagued with operating problems and was subsequently closed. On February 26, 1920, Smith formed Westend Chemical Company and with the assistance of Henry Helmers, a young chemist, they worked out a process based on carbonating and refrigerating brine. The first borax was produced in 1926, and the first soda ash in 1927. The plant was later expanded in 1955 to produce sodium sulfate. In 1956, the Westend Chemical Company merged with Stauffer Chemical Company, from whom Kerr-McGee Corporation acquired the facility in October 1974.

Development of the mineral potential of Searles Lake would not have been possible without transportation. The twenty-mule teams of John Searles were the first such means to haul borax out of the desert (U.S. Borax, 1972). His Borax Flat to Mojave route was replaced by the Trona Railroad. In 1912, Robert Ashton, working under the direction of Austin, who was receiver for the California Trona Corporation, was given the job of establishing a rail route into Searles Valley. Ashton worked east and north along the west shore of the lake to the site of the California Trona Company camp at Searles Lake. The railroad was originally called the "Three Elephant Route" as many of

the officers in the company were English with a background from India. They noted the long trains of mules used to haul freight across the desert, and claimed that elephants could have done the job better. This idea is the origin of the still-used brand name "Three Elephant Borax" for Searles Valley boron products. The Trona Railroad carries much of today's production of over 3 million tons per year, and also carries 360,000 tons per year of coal used as fuel by valley chemical plants.

## PRESENT OPERATIONS

### Lake Brine and Water System

Feed for North American Chemical Company's Searles Lake Operations comes from brine-bearing evaporite horizons in Searles Lake. See Figure 7. These brines are produced from the evaporite horizons by a system of wells and pipelines for each plant. Each system is designed to produce the best brine available for the plant it supplies. In some cases, solar ponds concentrate brine to increase plant production. In other cases, effluent is injected into an evaporite horizon to manufacture brine by solution mining.

Brackish water for plant use is obtained from a system of wells and pipelines located on the north, west, and south sides of Searles Valley. The wells are completed in the alluvial sands and gravel beds that surround the salt body. Because there are no fresh water sources in Searles Valley, other than minor springs in the Argus Range, fresh water is piped in from Indian Wells Valley for industrial, as well as domestic use. The fresh water system consists of two pipelines and five wells.

### Trona Main Plant Cycle

The main plant cycle consists of three major processing plants. These are the evaporator, the potash plant and the borax plant. Brine from the lake first travels to the evaporator where water is removed by boiling. Sodium chloride and borate are then removed by crystallization. The potash plant quickly cools hot concentrated liquor from the evaporator, causing KCl to crystallize. Cooled liquor from the potash plant is fed to the borax plant, where it is held while borax crystallizes. The hot liquor from the borax plant is mixed with the brine stream feeding the evaporators. Part of the KCl solids and the potash liquors are used to produce  $K_2SO_4$  in a secondary plant.

### Trona LLX-BAX Solvent Extraction Plant

Low quality lake brine is feed for the LLX-BAX processing plant. Boron values are extracted from brine into an organic extractant, which complexes the boron values as sodium or potassium metaborate. Boron, sodium, and

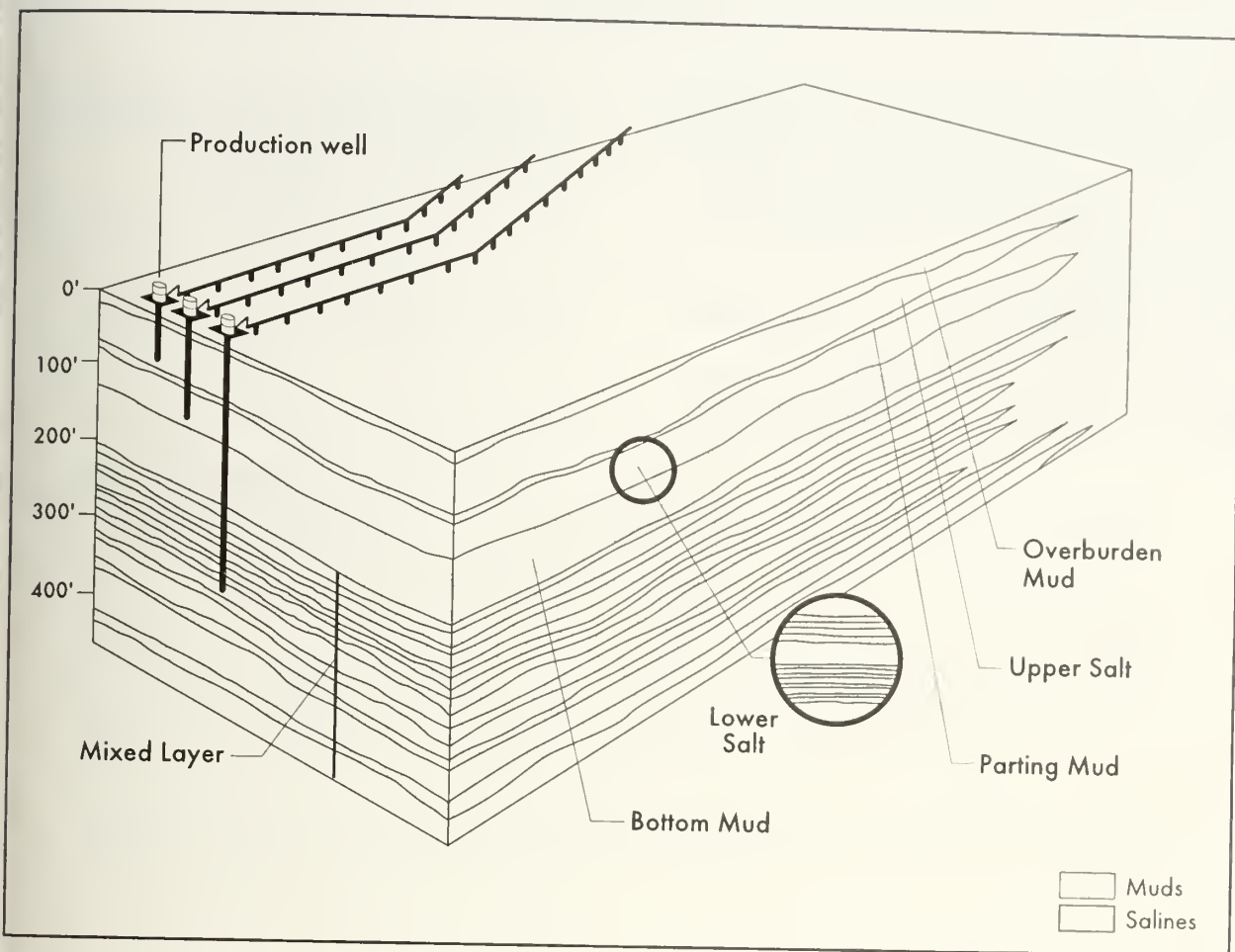


Figure 7. Solution Mining.

ssium values are then extracted into water by dilute sulfuric acid. This is evaporated and crystallized to produce potassium sulfate, and mixed sodium and potassium sulfates. Mixed sulfates are a feed for the secondary  $K_2SO_4$  plant.

### Argus Plant

Argus plant feeds are Mixed Layer brine, burkeite solution from the main plant cycle evaporator and Lower Salt brine. All three feed materials are reacted with carbon dioxide gas to precipitate the less soluble sodium carbonate. This is removed by filtration. Filtrates from Mixed Layer brine and burkeite solutions are returned to the main plant cycle. The Lower Salt brine is processed separately, so that the bicarbonate filtrate can be processed at Westend for borax and sodium sulfate recovery. Sodium bicarbon-

ate filter cake is dried, decomposed, bleached, recrystallized and redried to yield dense soda ash.

### Westend Plant

Carbonated Lower Salt brine from Argus is blended with a fraction of raw lake brine, refrigerated in seeded crystallizers, to recover crude borax, and refrigerated further to recover sodium sulfate decahydrate. Both intermediates are further refined to finished products.

### Dredging

The near surface trona rich beds found along the western edge of the Upper Salt are mined with a bucket wheel dredge. The dredged material is stacked to drain off excess brine, and air dried, before being crushed and shipped to the customer by truck.

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# Geology and Mining of the Miocene Fish Creek Gypsum in Imperial County, California

by  
Roger D. Sharpe<sup>1</sup> and Greg G. Cork<sup>2</sup>

## ABSTRACT

The United States Gypsum Company operation at Plaster City, in Imperial County, California, consists of the largest gypsum quarry in the United States, a company-owned, narrow-gauge railroad and wallboard and plaster manufacturing facilities. A variety of gypsum products, including many types of wallboard, construction plasters, portland cement setting agent, and agricultural gypsum are manufactured.

Gypsum is quarried from the Miocene age Fish Creek Gypsum. Evaporite minerals were deposited in a clastic-rich sabkha environment along the margin of a small embayment in the Salton Trough. The Salton Trough is a major regional structure that formed by rifting and transform faulting along the Elsinore, San Jacinto, and San Andreas fault zones. Sedimentary basins were formed between tilted fault blocks. The basins were filled by prograding alluvial fans, basin margin sabkha and marine sediments, and deltaic deposits from the Colorado River.

Gypsum is exposed in the quarry on rounded hills with 250-300 feet of relief. The evaporites are up to 200 feet thick and average 125 feet in thickness. Anhydrite commonly occurs in the lower part of the evaporites under the crests of hills and beneath thick alluvial cover.

## INTRODUCTION

### Location

The United States Gypsum Company operates a gypsum wallboard and plaster manufacturing facility and gypsum quarry in Imperial County, California. The operations are located about 100 miles east of San Diego, near the town of El Centro (Figure 1) in the Imperial Valley.

Gypsum wallboard, plaster products, portland cement setting agent, and agricultural gypsum are manufactured at Plaster City, located about 17 miles west of El Centro. Gypsum is quarried and crushed about 26 miles south-northwest of the manufacturing plant near Ocotillo Wells. Crushed gypsum is transported by a company-owned, narrow-gauge railroad from the quarry to the plant. The quarry produces about one million tons of gypsum per year.

### History

Gypsum was discovered in the Fish Creek area of the Imperial Valley during exploration for oil in the early 1900s. However, the deposits were not described in the U.S. Geological Survey (U.S.G.S.) compilation of gypsum deposits in the United States in 1904 (Adams, 1904). Stone (1920) only briefly mentioned the Fish Creek Gypsum deposit in the next U.S.G.S. survey of gypsum deposits in the United States:

A deposit of gypsum occurs in the hills 30 miles west of Brawley, close to the San Diego County line. '...' The gypsum is closely related to an occurrence of celestite and is said to be very thick. Reports indicate a massive rock gypsum, of good quality, 200 feet or more thick, making a narrow ridge nearly one mile long.

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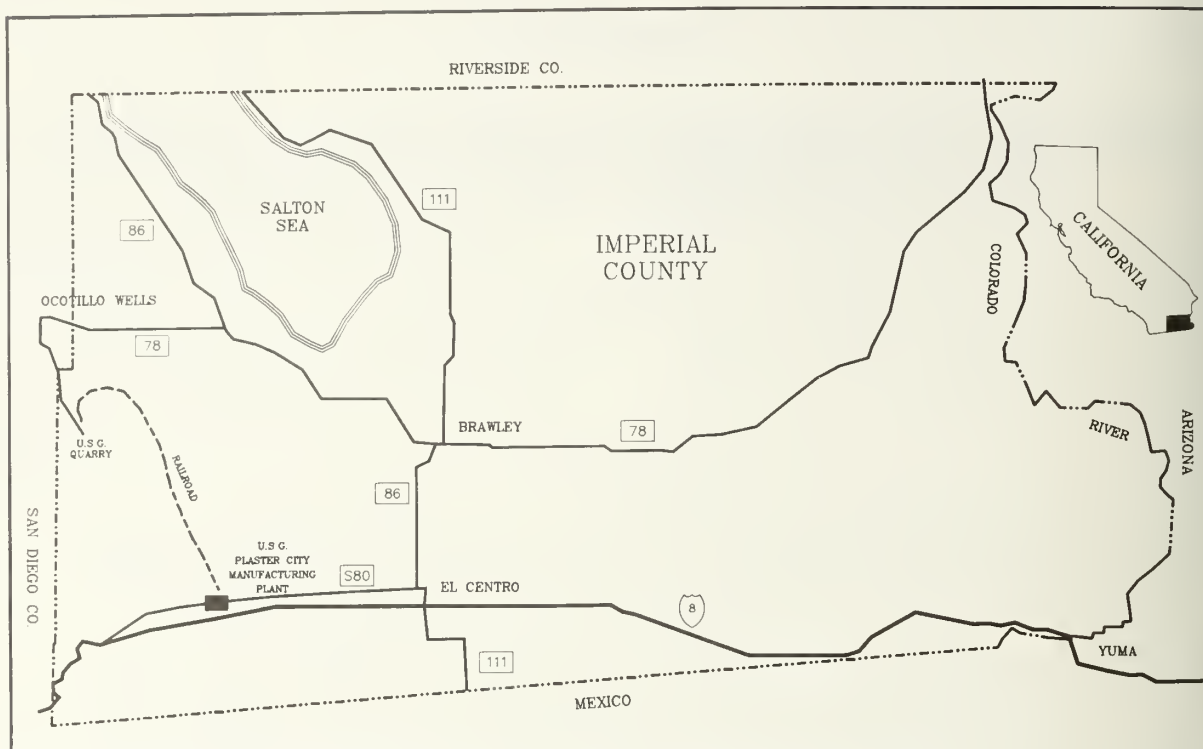


Figure 1. Location of the United States Gypsum Company operations in Imperial County, California.

A businessman from El Centro organized land holdings in the Fish Creek area under the name of Imperial Valley Gypsum and Oil Company in 1920. A crushing and pulverizing mill were constructed at the site of the present manufacturing plant. Construction of a narrow gauge railroad linking the Fish Creek deposit to the mill was completed in 1922.

The mill, quarry, and railroad were sold to the Pacific Portland Cement Company in 1924. Pacific Portland operated the properties for the production of gypsum for use as a setting control agent in portland cement. The United States Gypsum Company purchased the operation in 1945.

## USES OF GYPSUM

Gypsum is used to manufacture a great variety of products. Three major groups of uses for raw or processed gypsum are: (1) construction, (2) industrial, and (3) agricultural.

### Construction Uses

By far, the largest use of gypsum is in the manufacture of construction products. The thermal properties of gypsum products are important in the construction industry. Gypsum is used to make many types of gypsum wallboard and plasters for residential and commercial construction. The advantages of using gypsum wallboard include: (1) fire protection, (2) sound control, (3) low in-place cost, and (4) dimensional stability.

Additives, such as vermiculite, fiberglass, and asphalt emulsion are used in the manufacture of gypsum wallboard to impart greater fire or water resistance. Fire-resistant wallboard is used to retard the spread of fire between multi-family housing units or between garages and living spaces in single or multi-family housing. Water-resistant wallboard is used in areas of high humidity, such as bathrooms, kitchens and utility rooms. Water-resistant wallboard is also used, in conjunction with special adhesives, as a base for the application of ceramic and plastic tiles.

Gypsum wallboard has largely replaced plaster for covering interior walls and ceilings. The high demand for housing and ease of installation advanced the use of wallboard after World War II. Plaster was traditionally applied in several coats over metal or wood lath. Modern plasters have been developed for application over expanded metal lath or gypsum wallboard substrate. These plasters are formulated for ease of application, durability, and resistance to shrinking and cracking.

Gypsum is used to manufacture fireproof coatings for structural steel, linings of elevator shafts and poured concrete decks for commercial construction applications. Non-structural curtain walls and movable office partitions are constructed of gypsum wallboard. The partitions are often covered by decorative, durable, textured vinyl coatings.

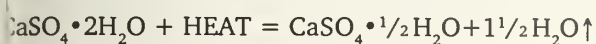
## Industrial Uses

### Uncalcined Gypsum

Uncalcined gypsum is used in a variety of products. Gypsum is ground with clinker to form portland cement. The addition of variable amounts of gypsum to clinker modifies and controls the setting characteristics of portland cement. Very high purity, finely ground gypsum is known as **Terra Alba**. Terra Alba is used in foods as an extender and calcium supplement in bakery products. Terra Alba is also used as a dilutant and extender in the manufacture of pharmaceuticals.

### Calcined Gypsum

Calcining removes part or all of the two molecules of water of crystallization in the structure of gypsum. The chemical reaction that takes place during the calcination of gypsum is shown below:



The largest use of calcined gypsum for industrial products is as a molding material for the production of ceramic sanitary ware, such as sinks and toilets, pottery, dental casting, and the production of decorative objects. Dental plasters are used to make casts or impressions for dental appliances, such as dentures and crowns.

Gypsum cements are produced for use in the oil industry. Quick setting gypsum-based cements are used to quickly seal oil and gas wells. Calcined gypsum is also used to produce high density, high strength patching material for concrete floors, highways, airport runways and taxiways. The patching material sets quickly allowing use in areas that cannot be closed down for conventional concrete repairs.

Calcining to a temperature of about 400°F produces "soluble anhydrite," which is used as a desiccant and as a carrier for certain types of insecticides. Calcining to a temperature of about 900°F produces **dead-burned gypsum**, or "insoluble anhydrite." Dead-burned gypsum products are used in the manufacture of rubber, artificial leather, plastics, paper, and pigments. Dead-burned gypsum is also used in the beer-brewing industry.

## AGRICULTURAL USES

Finely ground gypsum, known as **landplaster**, is used widely in the agricultural industry. The primary uses are: (1) improve soil drainage and porosity by breaking up compacted clays, (2) supply soluble calcium, and (3) neutralize the effects of sodium in alkali soils and irrigate waters by ionic exchange of calcium for sodium. Calcium is also often present in soils as expansive clays, such as bentonite and sodium montmorillonite. Gypsum is also used as an ingredient in feed for livestock.

## GEOLOGIC SETTING

The geological structure and stratigraphic relationships of the Fish Creek Gypsum and associated sedimentary rocks have been studied by many geologists. Notably, Winker (1987), Dean (1988), Kerr (1982), and Pappajohn (1980) have studied and mapped the area surrounding the United States Gypsum Company quarries. Their work forms the basis for the following description of the geologic environment.

### Regional Geology

The Fish Creek Gypsum deposit is located in the Salton Trough, a large topographic depression, located east of the Peninsular Ranges (Figure 2). The Salton Trough is a fault bounded basin which was formed during the rifting of the North American plate. Collision of the continental plate and the East Pacific Rise spreading center initiated the rifting (Sheehan, 1986). The development of the trough has been controlled by several northwest-southeast trending, right-lateral, transform faults. The Elsinore and San Jacinto faults bound the crustal block that includes the Fish Creek area. The Salton Trough is tectonically active and experiences frequent earthquakes. Geothermal activity is due to the near surface emplacement of sheeted dike swarms. The dike swarms have been intruded along "leaky" transform faults near an active spreading center (Elders and others, 1986). The trough was eventually filled by terrigenous sediments derived from uplifted fault block mountains, marine sediments deposited from a transgressing sea, Colorado River deltaic sediments, and recent alluvial fan deposits.

The Salton Trough is separated from the Gulf of California by a drainage divide with a maximum elevation of about 46 feet above sea level. The Colorado River currently flows into the Gulf of California. However, the river periodically changed courses, alternatively flowing into the Salton Trough and into the Gulf of California.

The Salton Trough was filled during the Miocene-Pliocene by the transgressing sea and several times during the Pleistocene-Holocene by the Colorado River. Remnants of late Pleistocene shorelines exist up to 500 feet above sea level (Winker, 1987). The elevation of these remnants may be due to continued tectonic uplift. Lake Cahuilla occupied the trough from A.D. 900-1400. Well defined strandlines, non-tidal landforms, and non-marine sediments represent several periods of trough filling by the Colorado River (Maloney, 1986). The Salton Sea represents the most recent flooding of the Salton Trough. The Salton Sea was created in 1905-1907 when the Colorado River flowed into the trough due to a breach in irrigation floodgates near Yuma, Arizona (Lindsay, 1988).



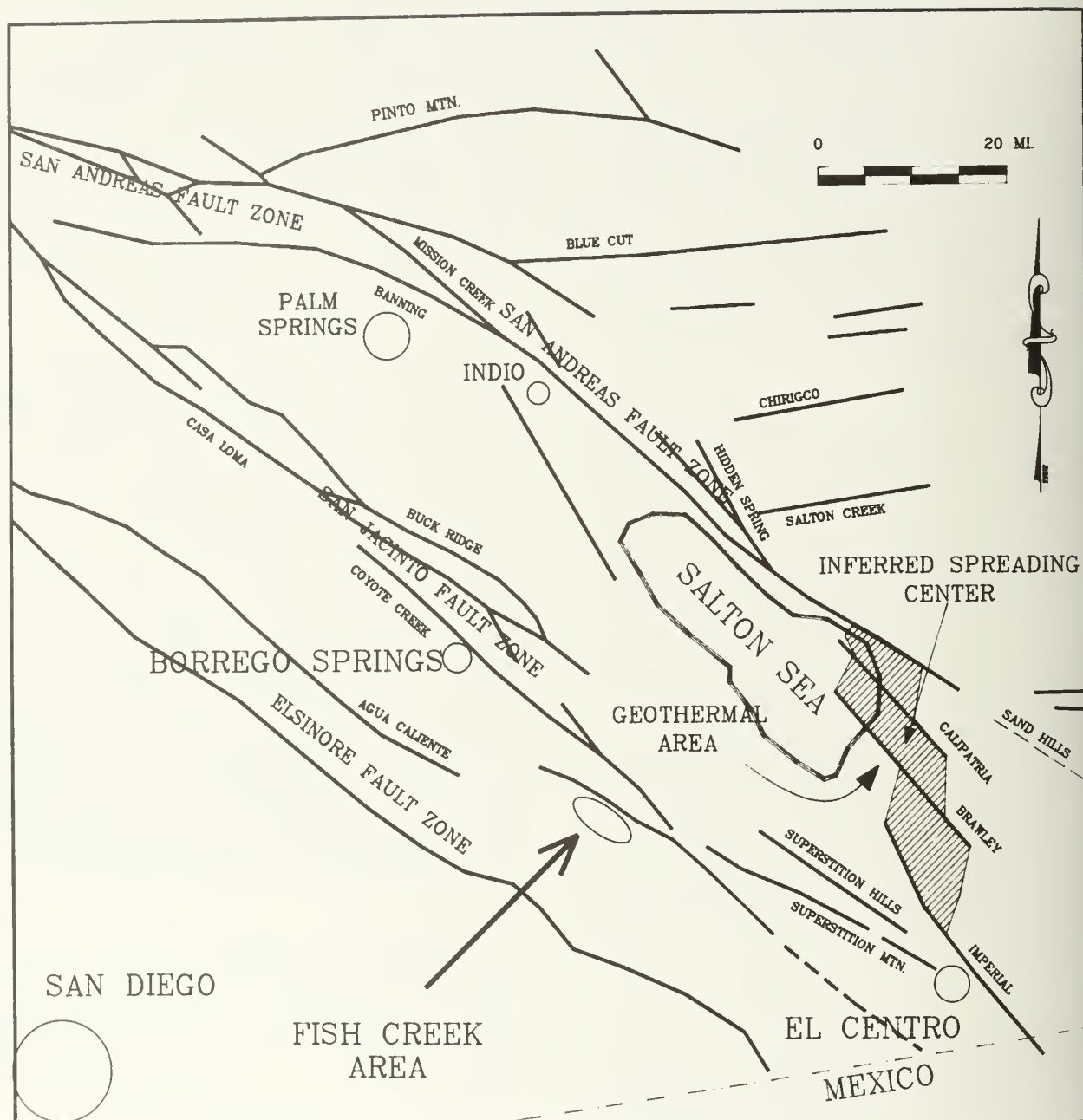


Figure 2. Regional structural features of the Salton Trough (after Gath and others, 1986).

## GEOLOGIC HISTORY

At about six million years ago (mya) the Gulf of California had reached northward to the location of the present Colorado River delta. In the Fish Creek area, the depositional regime consisted of braided streams that flowed over an eroded surface of Cretaceous crystalline basement rocks.

During the early to middle Miocene, asymmetric basins were formed between the faulted crustal blocks in the Salton Trough rift valley. The basins were quickly filled by very coarse-grained alluvial fans that prograded

over the younger braided stream deposits. Subaerial landslides, triggered by seismic activity, covered some of the alluvial fans.

By about 5.5 (mya) the Salton Trough had subsided enough so that the Gulf of California encroached northward into the Fish Creek area. The depositional basin for the Fish Creek Gypsum was a semi-restricted embayment along the margin of the Salton Trough.

Evaporites were deposited in a clastic-rich, coastal sabkha environment along the margin of the semi-restricted basin. The source of brines for the depo-

on of evaporites was the transgressing sea. In some areas, evaporites were deposited directly on crystalline basement. In other areas, evaporites were deposited on thick subaerial landslide deposits.

At about 4.3 mya the basin restriction was disrupted and the deposition of evaporites ceased. The evaporites were covered by shallow marine sediments, including mudstones and subaqueous debris-flows which were deposited in a submarine fan complex.

Marine deposition ceased when the prograding Colorado River deltaic complex isolated the Salton Trough from the Gulf of California. By about 2.8 mya, the Colorado River deltaic complex gave way to locally-derived terrigenous sedimentation and lacustrine deposits. The Miocene-Pliocene sediments were eventually buried to a depth of about 16,000 feet. Tectonic uplift which began about 900,000 years ago created the folds and faults in the Fish Creek area.

## STRATIGRAPHY

### Crystalline Basement

Nonmarine clastic rocks and evaporites are underlain by Mesozoic crystalline basement rocks. The generalized stratigraphy of the Fish Creek area is shown in Figure 3. The crystalline rocks include metamorphic rocks that have been intruded by plutonic bodies (verPlanck, 1952). Metamorphic rocks in the Fish Creek area consist of coarse-grained gneiss, mica schist, quartzite, and minor marble. The intrusive igneous rocks form batholiths with an average composition of tonalite.

### Split Mountain Formation

The oldest sedimentary rocks are a thick complex of terrigenous sandstone and conglomerate lying unconformably on the crystalline basement. The sediments were deposited in eastward prograding alluvial fans and are mapped as the Split Mountain Formation of Miocene age.

VerPlanck (1952) partitioned the Split Mountain Formation into a lower "red member" and an upper "gray member." Winker (1987) and other authors have extensively studied the Split Mountain Formation and subsequently repartitioned the formation as described below.

### Red Rock Member

The oldest sediments of the Split Mountain Formation consist of coarse-grained to conglomeratic, arkosic sandstones deposited from braided streams. The clasts are composed of local basement rocks, including quartzite, tonalite, pegmatite, and minor metamorphic rocks. The Red Rock member occurs as erosional remnants between the Elephant Trees Fanglomerate Complex and the underlying crystalline basement. The Red Rock Mem-

ber is about 600 feet thick along the crest of the Split Mountain Anticline, but is absent in the United States Gypsum Company quarry area.

### Elephant Trees Member

The Elephant Trees Member overlies the Red Rock Member and consists of a thick sequence of nonmarine fanglomerates, sheetflood deposits, and clast-supported conglomerates. The Elephant Trees Member thickens westward to a contact with a syndepositional, high angle, normal fault. The Elephant Trees Member is an eastward prograding alluvial fan complex deposited into the Fish Creek area prior to the encroachment of marine brines or sediments.

The lower fanglomerate sequence, formerly the "red member" (verPlanck, 1952), reaches a maximum thickness of 1,475 feet just west of the Split Mountain Gorge. An unnamed upper fanglomerate sequence, formerly the "gray member," directly underlies the gypsum on most of the United States Gypsum Company property. The thickness varies from nearly zero up to about 820 feet. The contact with the overlying gypsum is gradational. Green, arkosic, ripple-laminated sandstone is interbedded with gypsum in the lower few feet of the Fish Creek Gypsum.

### Lower Boulder Bed

Locally, the Fish Creek Gypsum is underlain by a clast-supported megabreccia with fragments up to 15 feet in diameter. The megabreccia formed from an air-lubricated, subaerial landslide triggered by seismic activity. Megabreccia deposits are absent in the United States Gypsum quarry area and varies from 165 to 500 feet thick in the Split Mountain Anticline.

### Fish Creek Gypsum

The Fish Creek Gypsum is a tabular deposit. The gypsum and associated anhydrite unit is up to 200 feet thick and averages about 125 feet in thickness. The upper contact of the gypsum is characterized by interbedded marine sandstones of the overlying Imperial Formation. The lower contact of the evaporites is gradational to arkosic sandstone of the underlying "unnamed fanglomerate." Locally, the gypsum is in direct contact with the underlying crystalline basement rocks.

Evaporite minerals were deposited in a coastal sabkha environment along the margin of a sub-basin or embayment of the Salton Trough. A sabkha is a wide tidal flat with a very low slope. The surface elevation of the tidal flat is controlled by deflation and the local groundwater level. The sabkha is formed in a hot, dry climate with high evaporation rates. The seawater is "pumped" laterally through the wedge of tidal flat sediments by evaporative reflux. High evaporation rates draw the pore water to the surface of the sabkha by capillary action. Diagenetic

AGE	NAME		THICK. (FEET)	DESCRIPTION
QUAT.	ALLUVIUM		400+	BASIN FILL AND ALLUVIAL FANS CONSISTING OF SAND AND GRAVEL
PLIOCENE	IMPERIAL FM	MUD HILLS MBR	3,000+	(1) SHALLOW MARINE GRAVITY- FLOW DEPOSITS.
		WIND CAVES MBR		(2) COLORADO RIVER TURBIDITE SEDIMENTS.
		UPPER BOULDER BED		(3) SUBMARINE MEGABRECCIA
		LYCIUM MBR		
MIOCENE	FISH CREEK GYPSUM		200	MASSIVE GYPSUM AND ANHYDRITE OF COASTAL SABKHA TO SHALLOW MARINE ORIGIN. GYPSUM IS TRAN- SITIONAL TO ANHYDRITE AT DEPTH
	SPLIT MOUNTAIN FM	LOWER BOULDER BED	165-500	AIR-LUBRICATED MEGABRECCIA LANDSLIDE DEPOSIT. ABSENT IN U. S. GYPSUM QUARRY AREA.
		UNAMED FANGLOMERATE	0-820	UNDIFFERENTIATED SEQUENCE OF FANGLOMERATE DEPOSITS. SAME AS "GRAY MEMBER" OF VER PLANK (1952).
		ELEPHANT TREES MEMBER	1,500	THICK SEQUENCE OF NONMARINE FANGLOMERATES, SHEETFLOOD DEPOSITS, AND CLAST-SUPPORTED CONGLOMERATES. INTERPRETED AS AN EASTWARD PROGRADING ALLUVIAL FAN COMPLEX
		RED ROCK MEMBER	600	CONGLOMERATIC ARKOSIC SAND- STONE DEPOSITED IN PALEO- DEPRESSIONS IN BASEMENT
	CRETACEOUS	UNCONFORMITY		THOUSANDS OF FEET
BASEMENT				

Figure 3. General stratigraphic section of the Fish Creek area, Imperial and San Diego counties, California.



minerals, such as gypsum, anhydrite, and carbonates, are precipitated when the pore water becomes supersaturated. Anhydrite is precipitated in the supratidal zone (above the mean high water level). Gypsum is the primary precipitate in the intertidal zone (between the mean low water level and the mean high water level). Anhydrite and gypsum grows interstitially by pushing aside the soft, fine-grained sediments. Upon burial, the gypsum may react with pore water to form nodules of anhydrite crystals. The great thickness of evaporites (up to 200 feet) has accumulated in approximately 1.3 million years in a degrading sabkha.

Post-depositional burial and high crustal heat flow has converted all of the gypsum to anhydrite. Recent uplift and exposure allowed groundwater to circulate through joints, fractures, and faults, converting the anhydrite to gypsum. Remnant anhydrite exists in the deeper part of the unnamed wash beneath thick alluvial overburden and Imperial Formation, as well as under the rounded hills in the gypsum outcrops.

The gypsum is remarkably pure, generally greater than 95 percent gypsum, with minor impurities of clays, carbonate, and detrital minerals. The highest purity gypsum is reserved for use in high quality industrial plasters and casting/molding products. The lower purity gypsum is used for the manufacturing of gypsum wallboard products. The following impurities have been identified by x-ray diffraction: clays, calcite, hematite, manganite, dolomite, quartz, biotite and feldspars. Celestite ( $\text{SrSO}_4$ ) is a common impurity and a trace amount of fluorite ( $\text{CaF}_2$ ) has been reported (Dean, 1988).

Clays occur as thin interbeds and as internodular matrix in the gypsum. Smectite and vermiculite are the most abundant clay minerals present, with minor amounts of illite, and kaolinite also present. The clays were originally deposited adjacent to the Fish Creek Basin in the tal portions of alluvial fans, then later reworked and deposited onto the sabkha surface during periods of flooding.

Marine fossils present within clays in the gypsum include: diatoms, calcareous nannoplankton, and diatoms, and spores identified in the sediments near the base of the gypsum include cottonsilk, sunflowers, Mormon Tea, bald cypress, spruce, wood, walnut, and hickory (Dean, 1988).

Black, purple, and rust stained patches occur locally within the gypsum. Black and purple stained samples generally contain organic material or manganese minerals. Rust stained patches may represent microenvironments of reduction due to the bacterial decay of vegetation grown into shallow lagoons on the sabkha surface.

## Imperial Formation

The gypsum is overlain by pre-deltaic marine sediments of the Imperial Formation. Locally derived shallow-marine and subaqueous gravity-flow deposits including a debris-flow megabreccia are present. Turbidites were deposited as submarine fans into a semi-enclosed basin. The Imperial Formation is exposed primarily on the southwest limb of the Fish Creek Syncline. However, the Imperial Formation has been encountered in drillholes in the wash down dip of the United States Gypsum Company quarries. Anhydrite is the predominant evaporite where the Imperial Formation is present in the subsurface.

## STRUCTURE

The main structures in the Fish Creek area are the northwest-plunging Fish Creek Syncline and Split Mountain Anticline, and northwest-oriented normal faults (Figures 4 and 5). Gypsum is exposed on the flanks of the syncline and anticline. Normal faulting has produced a series of southwest tilted blocks that exposed Cretaceous crystalline basement rocks and Miocene-Pliocene sedimentary rocks. Late stage folding and faulting occurred during regional uplift and rotation of basin fill and crystalline basement rocks.

Gypsum outcrops occur as rounded hills with a relief of 250-300 feet above the wash. The gypsum has been cut by northwest oriented normal faults and northeast and northwest oriented joints and normal faults. Normal faults within the gypsum have relatively small vertical displacements. The gypsum outcrops are separated by deep, fault/joint controlled ravines that expose the unnamed fanglomerate and crystalline basement rocks.

The northeast limb of the Fish Creek Syncline is bounded by a northwest oriented normal fault that dips steeply to the northeast. For most of its length the fault cuts basement rocks. However, a small remnant of gypsum and Elephant Trees Member is exposed on the hanging wall side of the fault at the northern end of the fault trace.

The southwest limb of the Fish Creek Syncline is bounded by another northwest oriented, northeast dipping normal fault. Crystalline basement rocks on the footwall have been displaced against crystalline rocks, Elephant Trees Member, and Imperial Formation on the hanging wall. The fault is in alignment with the axis of the Split Mountain Anticline. However, the fault possibly bifurcates with a northward extension that is parallel to the synclinal axis. The fault passes underneath alluvium on the west side of the wash. The other branch of the fault probably passes into the axis of the Split Mountain Anticline.

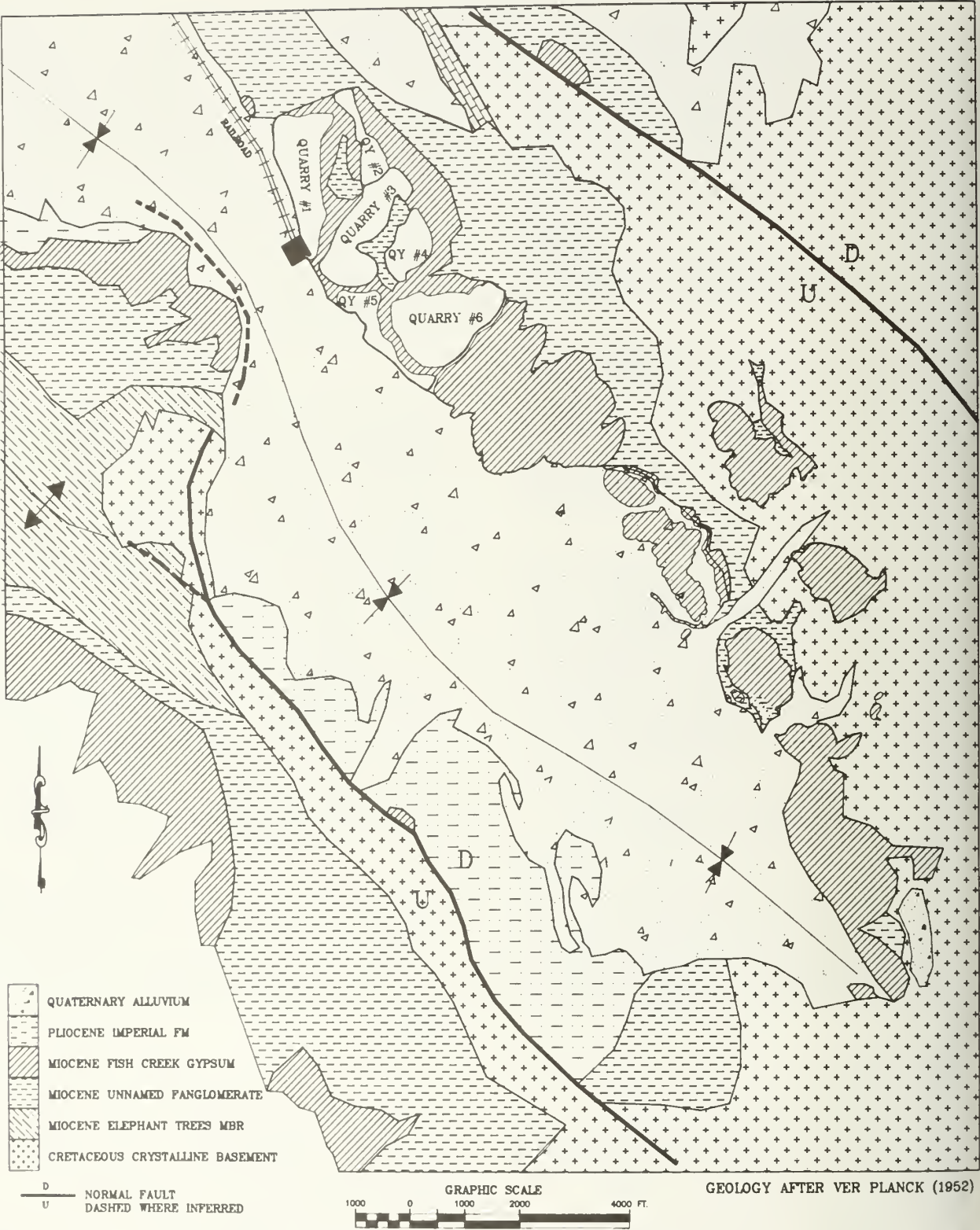


Figure 4. Geologic map of the United States Gypsum Company quarry operations in the Fish Creek area, Imperial County, California.



The evaporites dip into the wash at about 30°. Gypsum has been detected by drilling beneath as much as 375 feet of overburden. The gypsum is likely truncated against an unexposed portion of the normal fault on the southwest limb of the syncline (Figure 3).

The gypsum has internal structure including folding and low-angle thrust faulting. The bottom contact of the gypsum is relatively undeformed and dips uniformly for distances up to 1,000 feet. Radical changes in the attitude of the overlying gypsum occur over very short distances (Ver Planck, 1952). Gypsum is a highly plastic material which flows easily under the force of gravity. Deformation within the gypsum may have been produced by gravity flowage toward the axis of the syncline during uplift of the surrounding basement rocks. The effects of volumetric expansion (38%) due to hydration of anhydrite to gypsum that are exposed in the quarry include folds, enterolithic structures, and even small-scale, low-angle thrust faults.

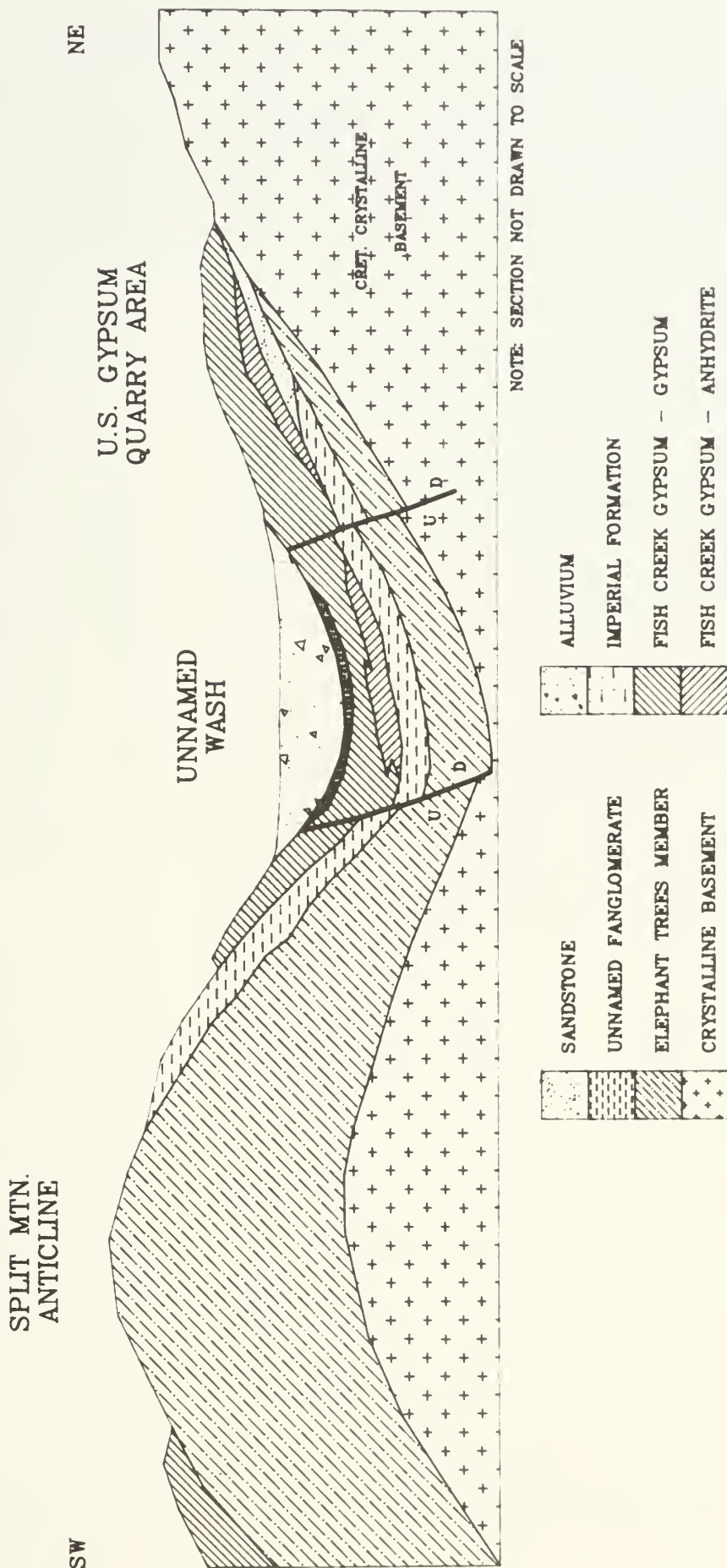


Figure 5. Schematic geologic cross section of the Fish Creek area, Imperial County, California.



## QUARRYING METHODS

The United States Gypsum Company operation consists of six quarry areas which have been worked since 1945. The quarries and crushing plant are located about 26 miles north-northwest of the manufacturing facilities, near the village of Ocotillo Wells. The current quarry is located about one mile from the crushing plant. Gypsum is exposed on a northwest trending series of rounded hills with a topographic relief of about 250-300 feet. The gypsum dips southwestward under Quaternary alluvium in the wash at an angle generally less than 30 degrees. Quarryable reserves occur on the rounded hill outcrops and under a maximum of 100 feet of alluvium in the unnamed wash.

Gypsum is extracted by conventional quarrying methods. The rock is drilled and blasted, then loaded into trucks for transportation to the primary crushing plant. The quarry employs a total of 21 people, including three in management/supervisory positions, 6 in maintenance, and 12 in production. The annual production of the quarry is about one million tons.

### DRILLING AND BLASTING

The surface of the outcrops is covered by a brown efflorescent crust of gypsum, called "gypsite," which is from 2 to 4 feet thick. The gypsite has a high purity but is soft, friable, and contaminated by wind-blown sand.

Benches are developed on the gypsum outcrops at an average height of 25 feet. The quarry uses two production blasthole drills, including a Gardner Denver RDC-16B and an Ingersoll Rand Drillmaster. A Pak Trak rough terrain drill is used for development. Blastholes are 4 3/4 inch in diameter and are drilled in a 14-foot by 14-foot staggered pattern. Up to 200 holes are drilled for each shot with each shot yielding about 70,000 to 80,000 tons. The drillholes are primed with a one pound cast booster and a 30 foot Nonel longlead cap. Bagged ANFO is used as the blasting agent. Apex 240 emulsion (3 1/2" x 16") is used in wet drillholes in lieu of ANFO. The drillholes are connected by 25 grain/foot Primacord detonating cord. Shot initiation is by blasting cap and safety fuse with a seven minute lead.

### LOADING AND HAULAGE

The crushed gypsum is loaded into quarry haulage trucks by two Cat 988B loaders with a bucket capacity of 6 1/2 cubic yards. The gypsum is transported to the primary crusher by four Cat 769C and one Euclid R35 haulage trucks with a capacity of 35 tons. The haulage distance is currently about one mile and cycle times average 18 minutes.

## CRUSHING

Quarry run gypsum is fed into two separate primary crushing and screening circuits depending on the product to be made. Gypsum rock used for the manufacture of wallboard and plaster products is dumped from the quarry haul trucks into a pan feeder for a 42 inch Traylor gyratory crusher. The bottom size from the crusher (-8 inches) passes to an inclined bucket elevator and then to a 4 inch primary screen. The oversize (+4 inch) goes to a 21 inch Traylor gyratory crusher with a bottom size of 4 inches. The primary screen undersize (-4 inch) goes to a stockpile feed belt, then to a 10,000 ton covered rock shed.

Gypsum rock to be used in manufacturing portland cement and agricultural gypsum is processed in a separate crushing and screening circuit. Quarry run gypsum is fed into a Stamler feeder-breaker with a 4 inch setting. From there the rock goes to a double deck primary screen. The top deck has 1 1/2 inch square openings and the bottom deck has 1/8 inch by 1 inch openings. The oversize from the top deck (+1 1/2 inch) goes to a Cedarapids swing hammer mill where it is reduced to minus 2 inches to dust. The output from the hammer mill is recirculated to the primary screen. The primary screen middlings (-1 1/2 inch to +1/8 inch) go to a radial stacker for storage on the portland cement stockpile. The undersize (-1/8 inch to dust) goes to the agricultural gypsum stockpile. The portland cement rock and agricultural gypsum stockpiles have belt scales and truck loading facilities. Final certified weights are determined on a 70 foot truck scale.

## RAILROAD

Gypsum is transported from the quarry to the plant by a 26 mile company-owned, narrow-gauge (36 inch) railroad. The unit train consists of up to 20 bottom dump open hopper cars with a capacity of 50 tons. The railroad is also used to transport potable water from the plant to the quarry by tank car.

The empty hopper cars are pushed into a tunnel beneath the covered rock shed for loading. Six hopper cars are gravity loaded simultaneously. Five loading chutes are used for loading gypsum for manufacturing wallboard. One loading chute is used for loading gypsum rock for use in making industrial plasters and molding, casting products. The trip from the quarry to the manufacturing plant takes about 90 minutes. At the manufacturing plant, the crushed gypsum is unloaded into a pan feeder-inclined belt system that feeds five silos, with a total capacity of 3,500 tons, or onto a stockpile.

## MANUFACTURING

### Milling and Calcining

The crushed gypsum is converted to finished products in a series of pulverizing and calcining processes. Gypsum is a hydrated form of calcium sulfate ( $\text{SO}_4 \cdot 2\text{H}_2\text{O}$ ). Pulverized gypsum is calcined to form calcium sulfate hemihydrate ( $\text{CaSO}_4 \cdot \frac{1}{2}\text{H}_2\text{O}$ ). This form is also known as **stucco** or **plaster of Paris**. Upon the addition of water, stucco hydrates and recrystallizes to form gypsum.

The calcining mill produces stucco for the production of wallboard and plaster products. Stucco is also produced to supply a United States Gypsum Company wallboard plant located in Santa Fe Springs, in the Los Angeles area.

The mill consists of secondary and tertiary crushing and calcining operations. Gypsum is fed from the silos or stockpile onto a double deck primary screen with a one inch top deck and a  $\frac{1}{8}$  inch bottom deck. The oversize material from the primary screen top deck (+  $1\frac{1}{2}$  inch) is sent to a 20 inch gyratory crusher with a bottom size of 10 inches. The undersize material from the primary screen ( $-\frac{3}{8}$  inch) is sent directly to the feed bins for the Raymond roller mills. The primary screen middlings ( $1\frac{1}{2}$  and  $-\frac{3}{8}$  inch) can be separated from the rock stream for use as portland cement rock. Portland cement rock is loaded into 100 ton rail cars or 25 ton highway trucks. Otherwise, the middlings are also sent to the Raymond roller mill feed bins. The gypsum is crushed to consistency of flour (-100 mesh) in six Raymond roller mills. The output from the Raymond mills is called **landplaster**.

At this stage the landplaster is split into two streams, one for feeding to the calcining kettles and the other for producing agricultural soil amendment gypsum. Calcining of landplaster to stucco is performed in six kettles. Five kettles are 10 feet in diameter and the other kettle is 5 feet in diameter. The output of stucco from the kettles is fed into hotpits for desteamming, completion of the calcination process, and then is stored in either; (1) silos for feeding to the wallboard manufacturing lines, (2) a 100 ton silo for rail loading for shipment to the Santa Fe Springs wallboard plant, or (3) silos for the plaster finishing operation.

### PLASTER

Plasters for use in residential and commercial applications are manufactured in the calcining mill, as described above. Plasters produced include IMPERIAL® plaster-coat finish, ZOU® plaster for fire-proofing structural steel, casting plaster, art plaster, dental plaster, and finishing plaster. The final products are bagged and palletized for distribution by rail and truck.

### WALLBOARD

The Plaster City plant consists of two wallboard manufacturing lines which produce a variety of products. The products produced include: (1) SHEETROCK® brand wallboard, (2) FIRECODE® brand fire resistant wallboard, (2) water resistant wallboard, (3) vinyl coated wallboard, (4) IMPERIAL® rock lath plaster substrate, and (5) elevator shaft liner.

Wallboard is produced by spreading a slurry consisting of stucco, water, and other additives between two continuous sheets of paper. An asphalt emulsion is added to produce water-resistant wallboard for use in areas of high humidity, such as bathrooms. Vermiculite and chopped fiberglass is added to produce wallboard with high fire resistance. All of the paper used by the United States Gypsum Company for manufacturing wallboard is produced from recycled paper. In addition, all of the paper is manufactured in company paper mills. The edges of the bottom sheet of paper are folded square around the soft stucco slurry core and a top sheet paper is applied. The edges of the wallboard sandwich are tapered while still soft to facilitate the application of joint compound and tape during installation.

The wallboard sandwich travels along a continuous conveyor belt until it is stiff enough to cut. During the trip along the conveyor belt gypsum begins to recrystallize forming a solid core. The needle-shaped gypsum crystals penetrate fibers in the top and bottom sheets of paper forming a tight bond. The wallboard sandwich is then cut by a rotary knife into standard lengths of 8 feet, 10 feet, 12 feet, or 14 feet. The standard thicknesses of wallboard are  $\frac{1}{4}$  inch,  $\frac{5}{16}$  inch,  $\frac{3}{8}$  inch,  $\frac{1}{2}$  inch,  $\frac{5}{8}$  inch and one inch. The sheets of wallboard are then flipped face up on an inverter table.

At this point in the manufacturing process the stucco has completely rehydrated to gypsum, but the wallboard still contains excess water. The wallboard is fed into a multi-deck, gas-fired, continuous kiln to remove the residual moisture.

The dried sheets of wallboard exit the kiln. Two sheets are flipped face to face, are trimmed to final length, and are taped together along the top and bottom forming a "bundle". The two-sheet bundles are mechanically stacked and then transported to a warehouse for storage. The final products are shipped to customers by semi-trucks or flatbed railcars.

Specialty products, such as vinyl or aluminum foil coated wallboard, are manufactured by laminating a coating to standard wallboard. Vinyl coated wallboard is used for interior partitions in commercial applications. Aluminum foil coated wallboard is used in applications where the foil coating acts as a vapor barrier to prevent interior moisture from entering wall and ceiling spaces.

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# The Boron Open-Pit Mine at the Kramer Borate Deposit \*

by  
Joe W. Siefke<sup>1</sup>

## ABSTRACT

The world-class Kramer sodium borate deposit is being developed by modern open pit operations near Boron, California. The deposit is a bedded, lenticular sedimentary sequence of borax and kernite crystals together with claystone. The borates dip south into a structural basin-bounding fault and were formed in the bottom muds of a permanent shallow lake. The lake was fed boron and sodium-rich solutions from a thermal spring source of volcanic origin. In addition to deposit geology, present day geotechnical concerns such as groundwater and slope stability will be discussed.

## INTRODUCTION

The Kramer borate deposit is located in the northwestern Mojave Desert, about 90 air miles northeast of Los Angeles and 3 miles north of the town of Boron (Figure 1). The deposit derives its name from the mining district in which it lies. The Kramer deposit, presently being mined from the Boron open pit, has been a world-class source of sodium borates since mine start-up in 1926 and continues to be the largest source of borates in the world. The Kramer ore body is a roughly lenticular sedimentary sequence of borax ( $\text{Na}_2\text{B}_4\text{O}_7 \cdot 10\text{H}_2\text{O}$ ) and kernite ( $\text{Na}_2\text{B}_4\text{O}_7 \cdot 4\text{H}_2\text{O}$ ) containing interbedded claystone. Its central crystalline facies is successively enveloped by facies consisting of ulexite ( $\text{Na}_2\text{CaB}_5\text{O}_9 \cdot 8\text{H}_2\text{O}$ )-bearing claystone, colemanite ( $\text{Ca}_2\text{B}_6\text{O}_{11} \cdot 5\text{H}_2\text{O}$ )-bearing claystone, and barren claystone. Studies indicate the Kramer borates were deposited in a small structural, nonmarine basin, associated with thermal (volcanic) spring activity during Tertiary time.

The Kramer deposit does not crop out. It was discovered accidentally in 1913 by Dr. John Suckow, a homesteader, who struck colemanite while drilling a water well (Figure 2). Exploratory drilling and shaft sinking after World War I by Pacific Coast Borax Company (PCB), the predecessor of U.S. Borax, led to the discovery of borax and kernite in 1925. In 1926 PCB went into large-scale, underground sodium borate mining in the Baker Mine, located nearly 2 miles east of Suckow's discovery well.

The company soon closed all its calcium borate operations near Ryan in Death Valley in favor of the more easily processed sodium borates at Boron.

U.S. Borax ships mostly bulk, refined sodium borate products and boric acid to both domestic and world markets from Boron. Principal uses for these products are in the manufacturing of glass and fiberglass, herbicides, ceramics, soaps and detergents, fluxes, fertilizers, and fire retardants.

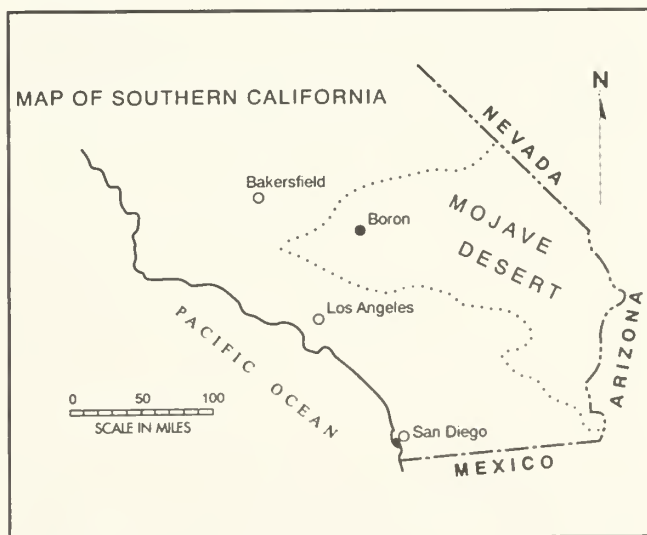


Figure 1. Location map.

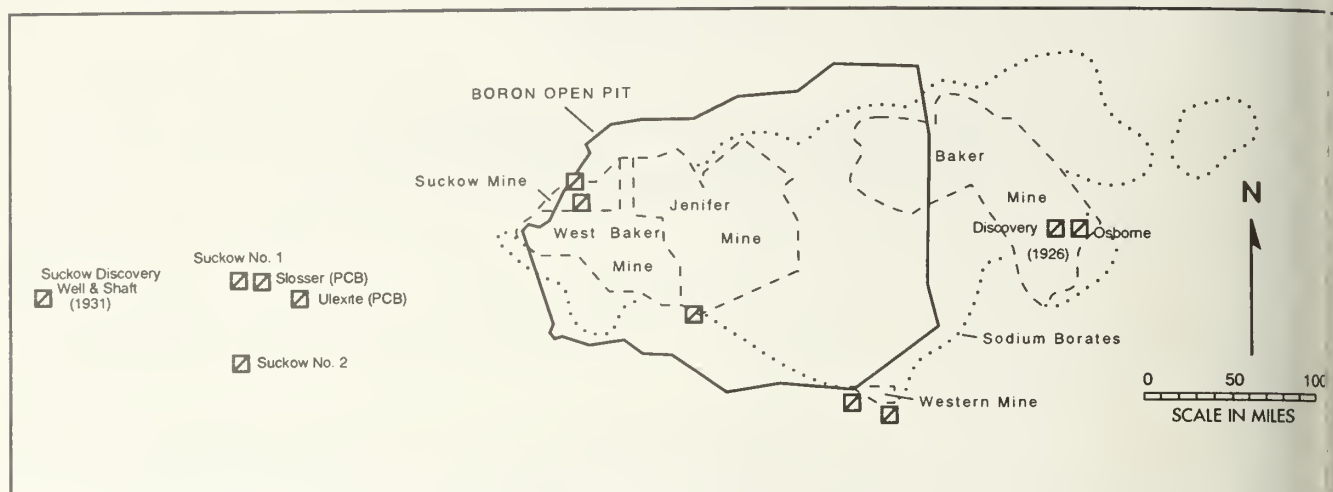


Figure 2. Kramer Borate District near Boron (development 1913 to present).

## MINING DEVELOPMENT

Development of borax and kernite in the Baker Mine was followed with the mining of kernite from the Western Mine (1927),  $\frac{1}{2}$  mile southwest on the south edge of the deposit, and the mining of borax from the West Baker-Suckow mines (1936), 1 mile west of the Baker. These early mines employed conventional underground room-and-pillar methods. By 1947 only the more easily processed borax was being mined, and soon most production was by continuous mechanical miners and belt haulage from the Jenifer Mine (1953), located in the central portion of the ore body,  $\frac{1}{2}$  mile west of the Baker. By 1956, with reserves of borax approaching exhaustion by underground methods, stripping was begun to achieve full borax ore recovery by open pit (1957), with feed to a new refinery.

Today, open pit stripping operations utilize 19-yard-capacity electric shovels and 170-ton trucks. Ore mining is routinely accomplished with 17-yard front-end loaders, a 20-yard hydraulic shovel, and 100-ton and 170-ton trucks. Round-the-clock, 7-day refinery ore-feed requirements have been met by a 5-day-per-week mining schedule. Approximately 10,000 tons of ore are mined, and 40,000 tons of waste are stripped daily. Late in 1994 the mining schedule will increase to 7-day operations to accommodate a 50% stripping increase. This change is necessary to meet exposed ore targets as waste-to-ore ratios increase.

The waste and ore alike are drilled and blasted. The waste is hauled to piles north and south of the pit. Borax ore is put through the pit 1,200-tons-per-hour (TPH) capacity primary-hammer-mill crusher (minus 8 inches), conveyed to the surface, blended in stockpile, recovered, secondary-hammer-mill crushed (to minus 1 inch), and put into the wet process refinery. Kernite ore is similarly

handled to a separate surface stockpile and fed to the boric acid plant (1980). Kernite ore is also pre-treated in a mid-open-pit plant by milling to minus  $\frac{1}{4}$  inch, hydrated in pit stockpile (converting kernite to borax), and blended with borax ores at the pit primary crusher or routine feed to the wet process refinery.

The present pit has surface dimensions of 6,000 feet long (east to west) by 5,000 feet wide (north to south). The greatest depth is 650 feet below original surface near mid-pit. Nearly all the workings of the two largest underground mines, the West Baker and Jenifer, have been consumed by the open pit. Future expansion of the pit will continue to be to the south (down dip) to develop molybdenum kernite ores and to the east, for borax ores.

Early pit engineering problems included slope stability affected by adverse geologic conditions, and a deposit honeycombed by underground workings that consisted of over 200 miles of single-cut headings. These and other concerns will challenge mine engineering in the future. Long-term mine plans indicate ultimate pit depths approaching 1,300 feet on the south. Deep pit conditions in moderately consolidated rocks raise concerns about slope safety and de-watering requirements. For the present, dry pit conditions and stable slopes on the south side are aided by use of the deep, underground workings of the Western Borax Mine as a drainage gallery. In addition, a number of wells located beyond the pit north wall maintain control on a pit-ward groundwater gradient. The present north wall (west-half) was excavated after the previous wall collapsed in 1985, due largely to adverse groundwater conditions.

Suckow's discovery site is nearly 1 mile west of the westerly pinchout of the sodium borates, and the early exploratory drilling penetrated only claystone-bearing ulexite and colemanite. Nearly 150 scattered surface

les and about 225 underground diamond drill holes are completed between 1913 and 1954. Since 1946 the all data collection in the sodium borates has been on an orderly 200-foot-centers grid pattern of surface holes. More than 675 modern mine-development rotary holes have been completed to date, utilizing in recent years a wire-line system to speed the core drilling in the deeply mined portions of the ore body. A core recovery of 98 percent has been routinely achieved. A number of recent holes have been located on 100 foot centers at faults for structural control. Information from many of the early holes and all of the more recent mine-development holes provide a data base for a deposit computer model. The deposit model was adapted from multi-seam coal deposit software, incorporating some of the important structural continuities of the Kramer deposit. Software is on hand to perform a wide variety of geologic and mine engineering functions.

## GEOLOGY

### Geologic Setting

The Kramer beds (Barnard and Kistler, 1966) are all conformable Miocene strata between the base of the Quaternary alluvium and the base of the Saddleback Basalt. The beds are of lacustrine and fluvial origin, as are other Tertiary nonmarine sedimentary and volcanic rocks of Dibblee's Tropico Group, exposed in the vicinity of Rosamond and Mojave, 30 miles to the west. General descriptions of the Kramer borate district are given by Dibblee (1946), Muessig (1956), Dibblee (1958), and Barnard and Kistler (1966).

Gale originally placed the Kramer strata in the Pliocene Ricardo Formation, which crops out about 29 miles to the northwest of the Kramer Deposit. Dibblee placed the Kramer beds into the early Pliocene of his Miocene and Pliocene age Tropico Group. In 1964 mammalian remains were discovered near the base of the Arkose member in the open pit. The fossils were identified as early Hemlockfordian, a pre-Ricardo fauna, no younger than early Middle-Miocene (Whistler, 1965), and were assigned an age of 19 to 20 million years. Subsequent potassium-argon (K-Ar) dates on samples of Saddleback Basalt yielded ages of 18.3 and 19.7,  $\pm$  0.6 million years.

The basement complex of the Boron area consists of deeply eroded pre-Tertiary (Jurassic?) granitic and metamorphic rocks. Older Tertiary arkoses, shales, and tuffs overlie the basement and are unconformably overlain by the Saddleback Basalt.

The following is a very generalized stratigraphic section of the units in the Kramer District in the vicinity of the sodium borate deposit, along with the maximum thicknesses exposed:

#### KRAMER DISTRICT NEAR BORON

	Feet
Recent alluvium .....	30
(unconformity)	
Quaternary alluvium .....	150
(unconformity)	
Miocene Kramer beds	
Arkose member .....	800
Shale member .....	400
Saddleback Basalt member .....	600
(unconformity)	
Miocene tuffs, tuffaceous shales, limestone, arkose and conglomerate .....	1,500
(unconformity)	
Pre-Tertiary (Jurassic?) granitic basement	

### Stratigraphy

As already stated, the Miocene Kramer beds are divided into three distinct members, the Saddleback Basalt member, the Shale member, and the Arkose member, in ascending order (Figure 3). The Saddleback Basalt comprises up to 600 feet of olivine basalt flows and is the only Kramer member forming surface outcrops--as ridges northwest, north, and northeast of the Boron open pit. The basalt is overlain by the Shale member, which consists of up to 400 feet of borate-bearing and barren claystones and shale. The Shale member will be discussed in some detail below. The Shale member is overlain by the Arkose member, which comprises up to 800 feet of arkosic sandstones which are locally silty and interbedded with tuffaceous clays. Figure 4 is a generalized geologic map of the Kramer beds as exposed in the Boron open pit mine.

The Kramer ore body is the core facies of the Shale member. Three additional facies and their relationship to the sodium borates will be discussed later. The ore consists of a lenticular sedimentary facies of borax and kernite together with varying amounts of interstitial and interbedded claystone. The sodium borates are roughly elliptical-shaped in plan, 2 miles in length (east to west), 1 mile in width, and range to a greatest thickness of 300 feet in the south-central portion. This sodium borate facies is divided into seven stratigraphic units, based upon detailed examination of drill logs and exposures in the underground mines and open pit. Four high-grade units, Upper Ore, Middle Ore, Lower Ore, and Basal Ore, typically contain over 75-percent borax. These are separated, respectively, by three generally low-grade units, A-zone, B-zone, and C-zone, which typically contain less



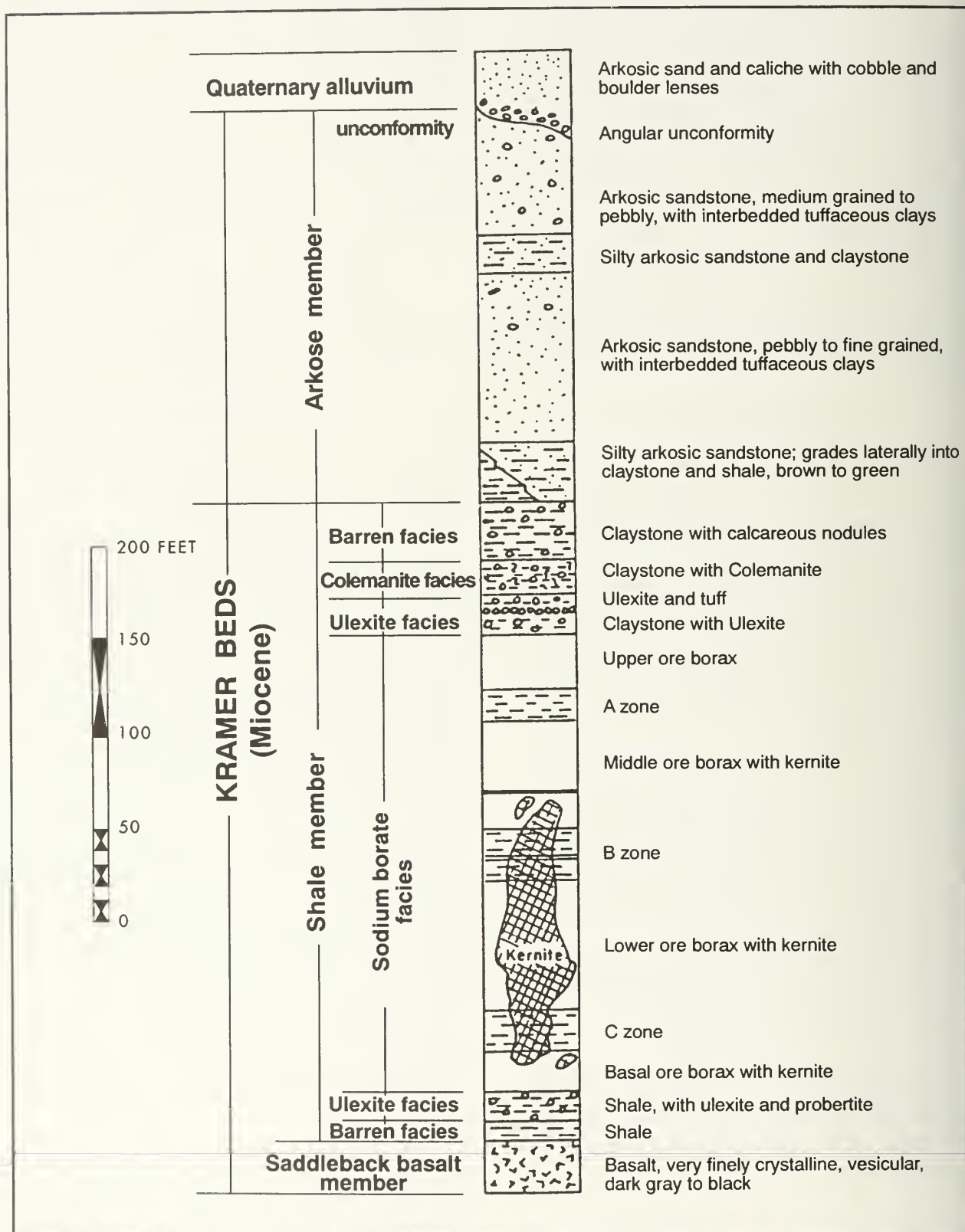


Figure 3. Generalized stratigraphic section of the Kramer beds.

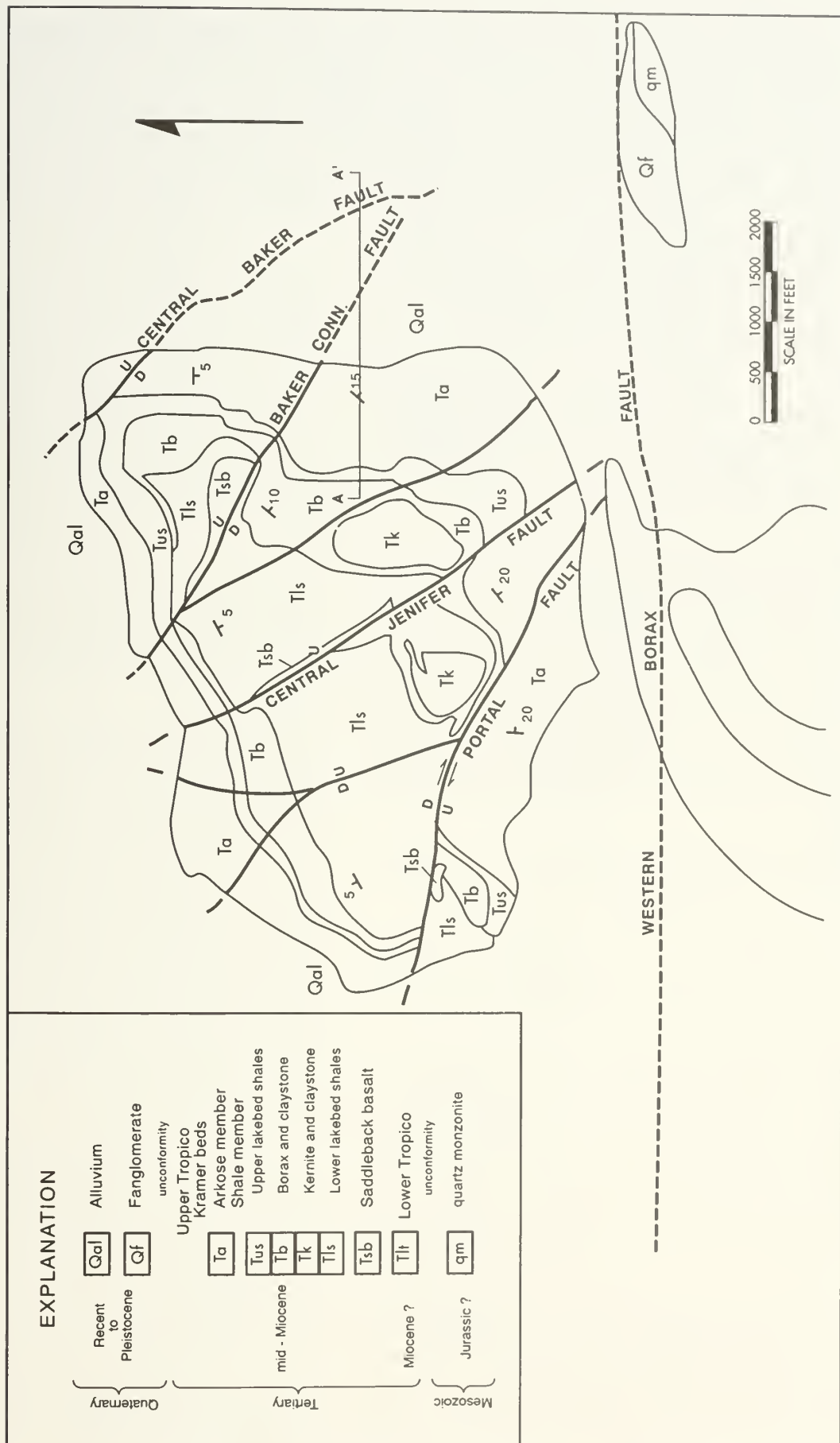


Figure 4. Geologic map of the Boron open pit mine area.

than 60-percent borax (Figure 3). The Basal Ore is the thinnest and least extensive of the high-grade units; the Lower Ore is the thickest and most extensive high-grade unit. Only in the thick central portion of the sodium borate facies, are all the units present. Stratigraphic control is maintained by use of a number of clay-tuff and claystone marker beds within the sodium borate facies.

Close inspection shows that borax crystals are commonly euhedral to subhedral, range in length from less than  $\frac{1}{8}$  inch to 1 inch, and are commonly stratified by crystal size. Borax makes up more than 80 percent of some high-grade beds, with claystone only interstitial to the crystals. In low-grade beds, borax makes up commonly less than 50 percent of the beds and is disseminated in a claystone matrix. Green to brown claystone beds of less than  $\frac{1}{2}$  inch to over 2 feet in thickness are commonly interbedded with the borax. Some of these, in addition to several prominent tuff beds, exhibit ripple marks and other evidence of shallow water deposition.

Much of the stratigraphically lower portions of the sodium borate facies consists of kernite, a secondary mineral formed by the dehydration and recrystallization of borax under conditions of elevated temperature and pressure. Christ and Garrels (1959) suggested kernite formation required deep burial ( $2,500, \pm 500$  feet) and a temperature range of 53 to 63 degrees C. The textures of the kernite ore are pegmatitic, with a crystal-size range from less than  $\frac{1}{2}$  inch to more than 5 feet in length. The crystals appear to be randomly oriented, in general, but locally show crystal-long axis parallel to relic (borax) bedding.

Claystone beds within the kernite are usually broken and distorted. Clay commonly forms rims around kernite crystals or is in irregular masses between crystals.

At the margins of the kernite occurrences, kernite is found in isolated pods and crystal masses. The pods commonly have a halo of recrystallized borax formed from rehydrated borax.

The Kramer deposit is the type locality for both kernite and probertite ( $\text{Na,CaB}_5\text{O}_{10} \cdot 5\text{H}_2\text{O}$ ). Probertite is found as radiating prismatic crystal aggregates, or rosettes, commonly within claystone and almost exclusively where kernite is the predominant sodium borate. Probertite was formed in the same environment of deep burial, as was kernite, and is much more abundant in the kernite deposit than is ulexite in laterally equivalent primary borax beds.

The sodium borate facies is successively enveloped by a ulexite facies, a colemanite facies, and a barren claystone facies. The ulexite facies consists of claystone, shale, and tuff, with ulexite occurring in beds, nodules, and veins. Several massive beds of ulexite up to 2 feet in

thickness, are associated with gray tuff and located stratigraphically above the sodium borate facies. Claystone and shale are much more abundant in the ulexite facies than in the sodium borate facies. A colemanite facies, thin interval composed of nodular colemanite and claystone, is found overlying and laterally beyond the limit of the ulexite facies. The colemanite appears to have replaced parts of the uppermost ulexite beds.

Around the outer part of the local basin of deposition is the barren facies; the beds of the colemanite facies grade outwardly into green shale and claystone, which contain calcareous nodules but are barren of borates. The gray-green to dark-green claystone and shale beds, common to all four facies, are montmorillonitic and occasionally tuffaceous. Individual tuff beds are traceable from one facies into a laterally adjacent facies. The boundary between the sodium borate facies and enveloping ulexite facies are quite sharp rather than gradational, and suggest, at least, minor solution activity.

## STRUCTURE

The shape of the sodium borate deposit in north-south section is lenticular with a southerly dip of about 10 degrees. The most deeply buried sodium borates are along the southern boundary near the Western Border Fault scarp.

The borates together with the overlying and underlying rocks, have been moderately folded and faulted. The deposit is divided by at least eight important west- and northwest-trending fault and fold structures. Both vertical and horizontal displacement have taken place along the faults. Most of the faults are steep, normal (vertical motion) faults of 30-percent to vertical dips. Pit exposures show most such structures to be faulted monoclinally with apparent displacement actually due to steeply dipping strata adjacent to the faults. Vertical offset on major faults displays pronounced differential, or "scissors," displacement along the fault trace. Only one important example of horizontal offset is evident--the Portal Fault, a west-trending fault which forms the southwestern deposit border. This fault exhibits about 2,000 feet of right-lateral strike-slip movement.

The fault-fold structures commonly exhibit structural and stratigraphic thinning. Structural thinning, due to minor dip slip offsets, is indicated along the trend of major faults. More than 400 feet of this offset is found on the Central Jenifer Fault. Stratigraphic thinning of the sodium borates adjacent to the northwest-trending faults is evident locally, especially on the up-thrown blocks (Figure 1). Some thinning along faults is due to post-emplacement dissolution of kernite and borax. Pit exposures at several faults exhibit bedding collapse, pseudomorphs, and other solution features which suggest removal of sodium borates by circulating ground water.



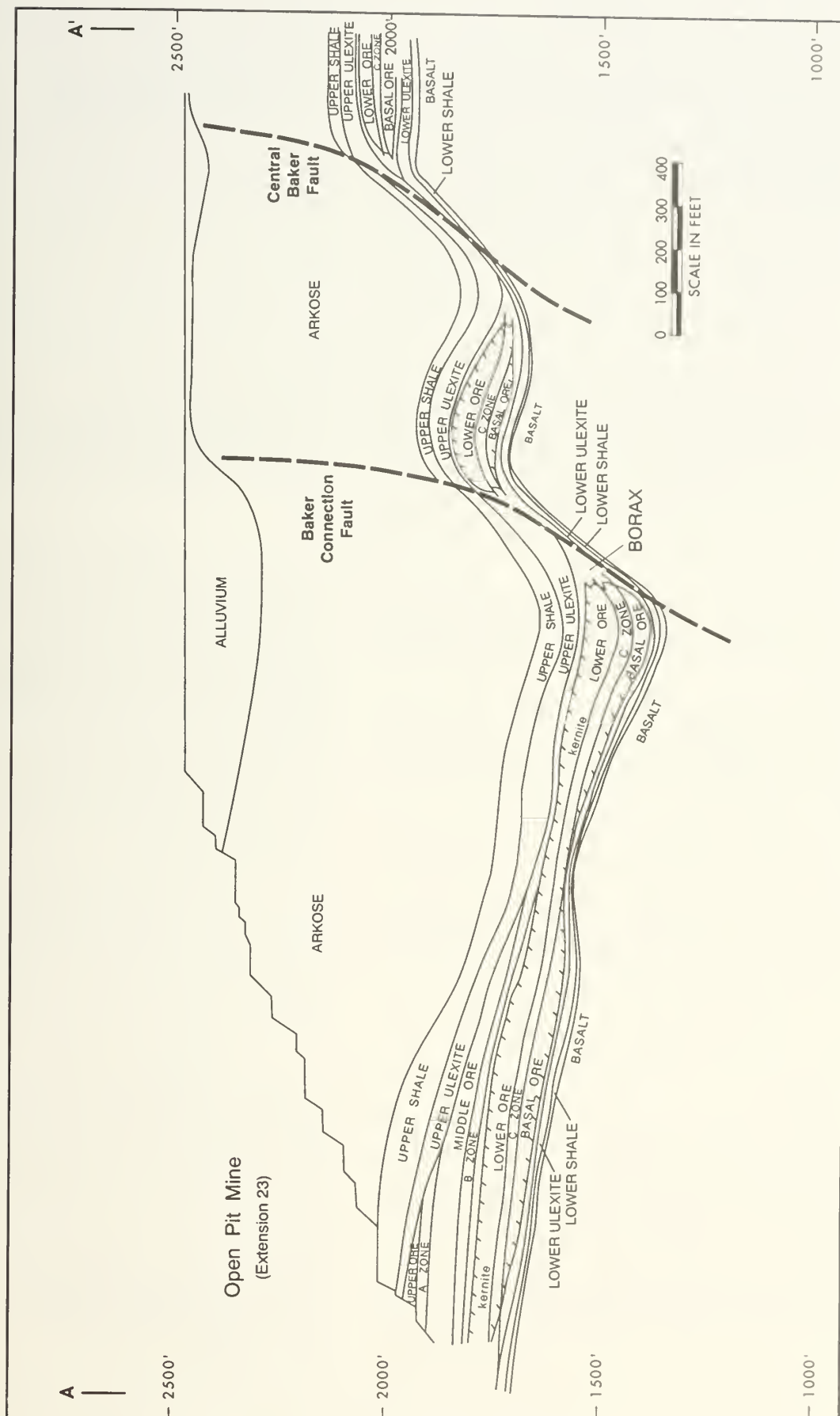


Figure 5. Geologic cross section A-A' (see Figure 4).

## Geologic History

The Kramer lake beds were deposited in an east-west-trending basin, which was formed by subsidence on the Western Borax Fault. After extrusion of the Saddleback Basalt, boron and sodium in waters from local thermal springs mingled with calcium-bearing surface waters and formed ulexite in the muds of a playa, located north of the fault. The clays of the deposit were derived as weathered products of the iron- and magnesium-rich volcanic rocks. Eventually, a lake formed in the central portion of the playa basin, and borax began to form on the bottom muds as a primary precipitate. Water from the thermal spring source, assumed to contain more sodium borate than the cooler lake water and, consequently, to be denser, flowed to the lake bottom, cooled, and precipitated borax. Lighter, near-surface water, bearing sodium chloride and other dissolved salts, overflowed at a low outlet. The lake was probably like modern lakes of the region, with temperatures ranging seasonally from 10 to 25 degrees C. Successive beds of borax crystals, protected by layers of mud, were progressively deposited as the basin continued to subside.

The formation of lower-grade units at three depositional intervals (A-, B-, and C-zones) was probably caused by climatic change or protracted periods of borax undersaturation.

Realgar (AsS) and stibnite ( $\text{Sb}_2\text{S}_3$ ), carried in solution from the hot spring source, were co-precipitated with the borax and at greatest concentration during the late stages of borax deposition.

As the basin gradually filled with borax and clay, the size of the lake varied, and the location of the deposit boundaries shifted. The early borax deposition was restricted to the southern and eastern portions of the ore body. The center of deposition shifted north in the mid- to late-stages. Deposition of the Lower Ore marked the period of greatest extent of the sodium borates.

During lakebed deposition, a minor amount of vertical movement occurred on the northwest-trending faults. This apparently resulted in less deposition of borax adjacent to the faults.

The last stages of the lake, after deposition of borax ceased, included deposition of ulexite and clay and, lastly, clay with volcanic ash. The lake phase came to a close as continued fault movement tilted and dropped the lake sediments and buried them under more than 2,000 feet of late Miocene and Pliocene arkosic sediments. During the period of deepest burial and maximum temperatures, kernite replaced borax as stratigraphically high as the Upper Ore, but nearly all the kernite was formed in those

units below the A-zone. Probertite formed contemporaneous with the kernite, probably by the reaction of calcium from dolomite in the clays.

Late in the middle Pliocene, during the uplift of the Mojave block, the Kramer beds were uplifted, folded, and faulted. This period included the greatest amount of folding and dip-slip fault activity on the northwest-trending faults. The uplifting resulted in the erosion of a thick sequence of upper Kramer sediments. As unloading of the borate deposit progressed, pressure and temperature were gradually reduced, and borax replaced kernite at the outer fringe of the kernite crystal mass and in narrow zones adjacent to the faults. Sucrosic borax filled most of the numerous fractures formed during tilting and folding of the deposit.

Following the most recent episode of uplift and erosion, alluvium was deposited on beveled Kramer beds during the Quaternary Period and Recent Epoch.

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# Geology of the Hector Mine Deposit

by  
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## ABSTRACT

The Hector Mine deposit in the California Mojave Desert has a magnesium-rich clay that formed when lithium and fluorine were introduced into isolated fine lacustrine volcanic sediment during the Pliocene. The intensely deformed deposit has been supplying the highest grade thixotropic clay to the coatings industry for over half a century. A thixotropic clay displays the property of changing from a gel to a sol when shaken, and increases in strength upon standing.

## INTRODUCTION

The Hector Mine is located 32 miles east of Barstow, California, and midway between Los Angeles and Las Vegas, Nevada. It is in the central portion of the Mojave Desert which is bounded by the San Andreas Fault on the west and the Garlock Fault well to the north. This--the Mojave Block (Dibblee, 1980b)--is the southwestern part of the North American Basin and Range Province. North-south oriented valleys and mountains throughout the block are cut by a north to northwesterly fault system.

Along with the very young Pisgah cinder cone the deposit is situated upon a slight topographic high separating the lineament of the east-west Barstow and Bristol troughs. To the north are the Cady Mountains while to the south is the Lava Bed Mountain; part of the Newberry Mountain.

## REGIONAL GEOLOGY

During the Mojave Uplift (Dibblee 1980a) of the Tertiary Period the central area of the Mojave Block was elevated. Material was eroded toward the western side exposing the granitic basement emplaced during the Franciscan Orogeny. During the Oligocene, failure of this basement initiated the development of the present basin and range geomorphology, and this region accumulated erosional material within the subsiding blocks. Dibblee (1980a) attributed a compositional change from intermediate toward the basaltic volcanics in the late Tertiary to a deepening of structural failure planes.

Two-to-three miles of middle Cenozoic volcanic flows, tuff-breccias and boulder conglomerates accumulated in the Central Mojave Block.

The rate of subsidence of these basin and range blocks had slowed considerably during the Pliocene when well-formed basins held a series of lakes collecting fine silts, sands and airborne tuffs from several remnant volcanic centers. The Barstow-Bristol Trough, one of the basin systems, held numerous broad, shallow lakes (Gardner 1980).

Several localized centers of Pleistocene volcanism existed in the desert. One just south of the study area, is the dissected basalt field of the Lava Bed Mountains. Another, covering the hectorite deposit is the extremely recent Pisgah flow.

## GENERAL STRATIGRAPHY

Drilling has repeatedly intersected a green hypersthene, augite porphyritic andesite. It has a thick (7-10m), weathered cobble surface. At the mine only 100-125 m of Pliocene lakebeds overlie the andesite. These beds may have been in the range of 500 m thick. Here they are calcareous and tuffaceous bentonite clays with numerous impure zeolitic bands. Within this unit is found the travertine and associated hectorite. The lakebeds and especially the hot springs deposits are intensely deformed. This deformation occurred prior to burial beneath the 10-30 m thick olivine basalt within the last several thousand years.

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Figure 1. Hector Mine, California, looking southeast.

## PLIOCENE LAKEBEDS

These bentonitic clays are chocolate brown to dark tan, massive units with varying hues of pink and orange. Variable amounts of tuffaceous sands, grit, carbonates and abundant zeolites emphasize a moderate bedding on weathered exposures. The zeolite seams are typically "gritty" due to incomplete alteration. Two rather pure beds of zeolite, 30 and 60 cm thick occur near the top of the sheared hectorite contact.

The damp, blocky bentonite clays are cut by many sets of joints and shear planes. Most are very tight. Within the noses of large folds are dogtooth spar pellets, (to 1 cm) as well as concretions (1-10 cm) of radiating calcite crystal growths.

## HOT SPRINGS DEPOSITS

Within the lacustrine bentonites and 15 to 30 m above the weathered andesites is the hot spring sequence. The various travertine and hectorite lenses are generally contiguous but outliers of each have been defined by drilling.

The cream to white travertine has tan and pink banding due to included laminae of very fine bentonitic volcanoclastics. Depositional features include sheet layering, mammillary texture, dripstone, and a honeycomb network. Brecciated travertine that has been rewelded is very common.

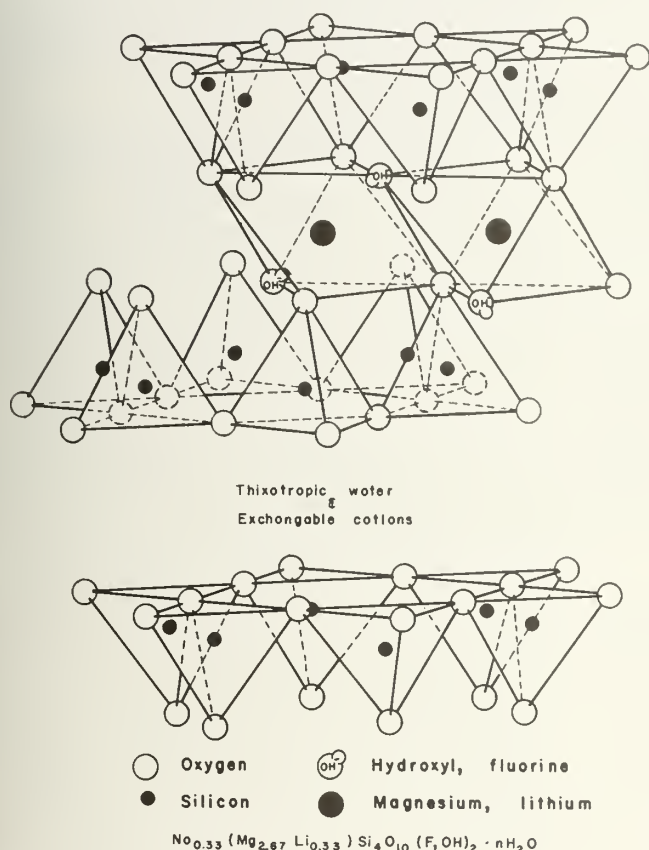


Figure 2. Atomic structure of Hectorite. (After Grim, 1962).

The pure hectorite, a soft, very pale grey to bluish-gray translucent clay resembles a piece of paraffin wax. An edge cut with a knife will curl in the same manner as a candle when warmed. A piece of the mined ore is cool and damp with 40 to 50% moisture by weight. It has a strength similar to that of paraffin wax in a warm room. When air dried to an 8 to 10% moisture content, the clay shrinks and crumbles to a gritty white powder.

Typically the hectorite is chalky white due to abundant diagenetic and recrystallized calcite. Dogtooth spar and radiating calcite crystal concretions concentrate in the nose of folds. Also included in the ore are smoothed and polished grains, spherulites, spheroids and occasional boulders of brecciated travertine. Most hectorite is sheared and plastically deformed. One dome-like plug 10 m in diameter was excavated. This had penetrated the more brittle overlying calcareous bentonite.

Laminar hectorite is common along the upper ore contact and varies from an olive green color to a grey color. Bentonitic clays had been thoroughly mixed by shearing of the hectorite along nearly flat-lying failure planes. These weak, green clays have a higher moisture content of 60 to 70%.

Very hard, medium dark, black, blue-gray and purplish-blue lobular quartz nodules with septarian interiors and "cotton rock" surfaces are localized in the ore. Some nodules have concentric shrinkage layers and others have hollow lobes. Multiple lobes are common with the typical lobe being about 7 cm in diameter.

## STRUCTURES

Striking northwesterly the still active Pisgah Fault passes within 90 meters of the producing E-pit (Figure 1). The fault trace is at least 35 km long with the mid-point near the mine. It is a right lateral, normal fault steeply dipping to the west. It generated a magnitude 5+ aftershock associated with the Landers earthquake in the summer of 1992 (Topozada 1993).

A secondary failure plane, parallel to the Pisgah Fault, passes through the southwest corner of the present pit. A minor playa has developed in the small subsidence block between the two faults 0.8 km northwest of the pit. The Pisgah Fault scarp is easily visible in the very Recent Pisgah flow. This fault is the likely feeder for the Pisgah Crater to the east and the Pleistocene volcanoes in the Lava Mountains to the south.

## MINERALOGY

Hectorite was first identified by Foshag and Woodford (1936), and later named by Von Strese and Hofmann (1941). This trioctahedral sheet mineral (Figure 2) has an octahedral layer sandwiched between two silica tetrahedral layers. Magnesium and minor lithium replace all of the aluminum sites while some of the hydroxyl sites are replaced by fluorine.

## Thixotropy

The morphological structure is of wide flat sheets that develop very strong thixotropic bonding. The sheets form a stacked mesh in water or select organic fluids to form gels. Energy imparted to a clay suspension results in a gel failure that reforms quickly after the shearing energy is removed. This thixotropic property is important in the coatings industry. At least three times as much darker bentonite is required to develop a gel consistency equivalent to that of hectorite, but without the thixotropic property of hectorite.



Christopher Guerre (1990) suggested that the better hectorite gels could be related to the amount of lithium substitution.

## DEPOSIT GENESIS

During the Pliocene pre-existing regional forces responsible for developing the Pisgah Fault caused an uplift of the structural block in the proximity of the Pisgah Crater. This interrupted the flow between the Barstow and Bristol troughs developing a large shallow lake that collected fine volcanic sediment and airborne ash.

Meteoric waters circulating along the Pisgah failure plane tapped residual heat from deeper intermediate intrusives emplaced during the Miocene. These waters carried soluble ions including lithium and fluorine to surface thermal springs at the eastern margin of a large shallow lake. An accumulation of travertine developed a ridge which diverted sediments around its extremities causing bars to be built out into the lake (Figure 3).

A regulated flow eventually developed between the marginal lagoon and the main body of the shallow lake. Magnesium rich alkaline lake waters slowly washed over the bar to mix with the lithium and fluorine supplied by the hot springs. The finer glasses and tuffs were selectively winnowed from the bars into this "chemical soup pot" and eventually altered into hectorite clays. Because of the high pH the aluminum and silica was kept in solution and eventually decanted out to the lake.

During periods of extended quiescence the hot spring vents sealed shut. With renewed thermal activity, pressures built within the geyser chambers causing an explosive brecciation that ejected fragments into the air. Continuing hot springs activity contributed additional carbonates that welded the brecciated heap together (T. Eyde, oral communication, 1984). Eventually the fumarole activity permanently stopped. Continued basin subsidence resulted in burial by typical calcium bentonites and later by other coarser sediments.

During the Pleistocene the ever deepening Pisgah Fault eventually reached a basalt source. The rising basalt magma contributed to further warping the area prior to exuding to the surface, first at the Sunshine Peak area of the Lava Mountains and then at the Pisgah Crater.

Subsequent compression and drag effects along the Pisgah Fault caused extreme deformation of the ore

deposit. The built-up stresses within the deposit were relieved with the plastic flow of the hectorite. Hydraulic pressures of the clay operated to fracture the more brittle travertine. The deposit became a sort of autogenous ball mill. Deformation of the bentonites outside the deposit were not as extreme.

## PROPERTY DEVELOPMENT

Just prior to and during the early years of the Great Depression, Oscar and Emery Hoerner, along with several other individuals, had successfully promoted and sold a group of bentonite properties located miles to the north-west. Continually searching for more properties containing drilling mud, they moved into the Hector area. From 1931 to 1934 they staked most of the area.

During 1937 and 1938 speculative transactions of the key hectorite property leases changed hands several times prior to development. Eventually in 1944 that portion acquired by the F.S. Schundler Eyrte Company was sold to the National Lead Mining Company which had acquired the North Group bentonite claims the year earlier. The other major player, the Inerto Company, was already in business having acquired their leases in 1941.

By 1948 The North Group bentonites were eventually depleted and National Lead Company, which became NL Chemicals and finally RHEOX, Inc., maintained a very vigorous competition with the successful Inerto Company. The former company took over the Aquagel paint market while the Inerto Company developed the very successful Tansul used to clarify most beers and ales in the world.

The companies mining underground on opposite sides of the same ore body joined workings during 1961 to develop a safe ventilation system. Within months of the breakthrough a flash flood, which entered the lower Inerto shaft also flooded out the National Lead working through this join. Having just begun a small open pit National Lead Company was still able to supply its customers. Inerto could not, and was forced to sell.

Since that time mining has continued with truck and loader open pit methods. This allowed for recovery of many of the remaining ore pillars. The present pit extends south from the original underground workings. This deposit has been continuously mined for more than fifty years and is planned to continue well into the next century.



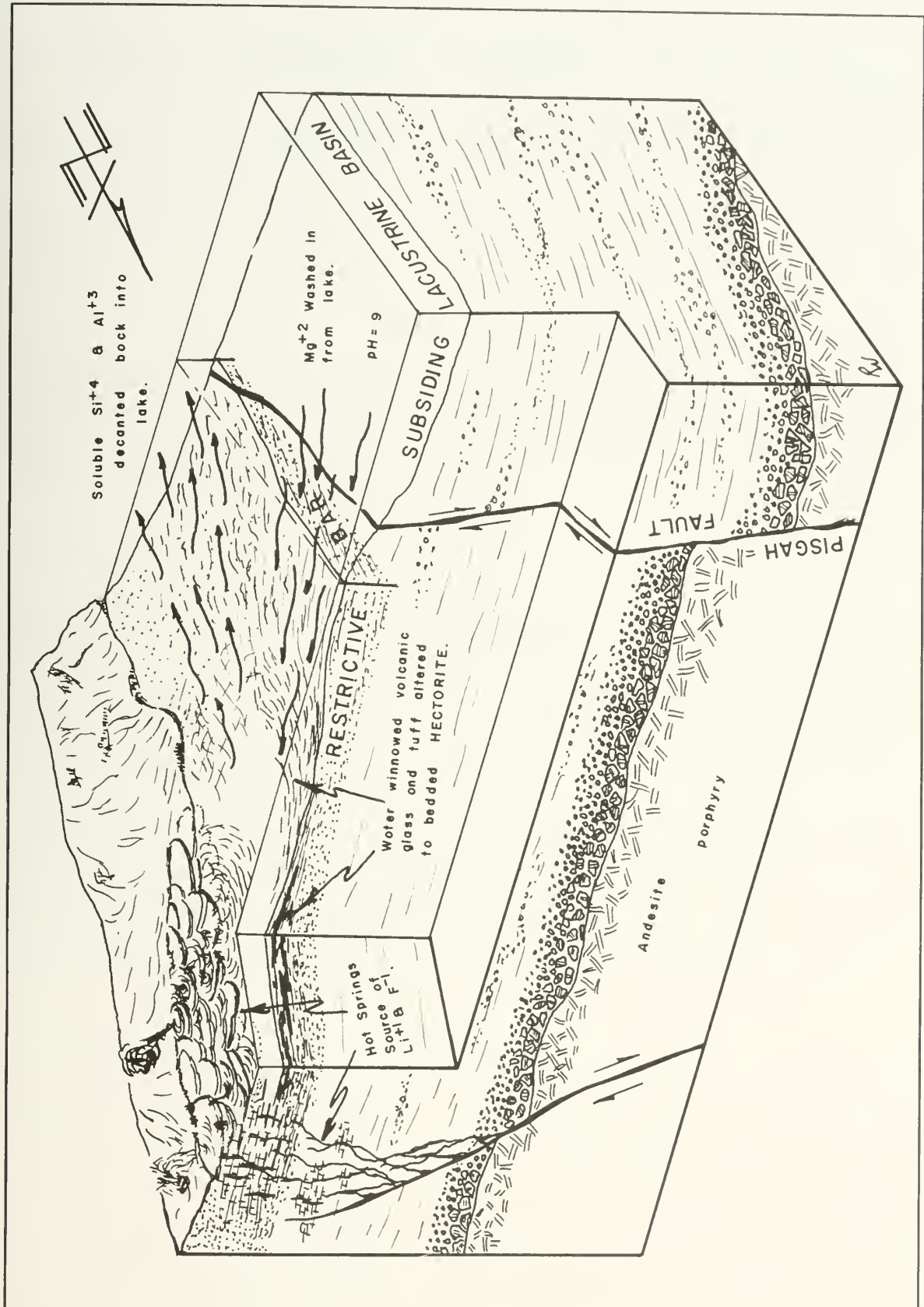


Figure 3. Idealized environment of the formation of Hectorite at Hector, California

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# The Mojave Desert Province Southern California: Geologic Overview

by  
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## ABSTRACT

The Mojave Desert province is comprised of a diverse group of mountains that range in elevation from about 2,000' (600 m) to 3,000' (900 m), separated by tracts of alluvial cover. The province is bounded on the southwest by the San Andreas fault, on the north by the Garlock fault, on the east by the Death Valley- Granite Mountains fault. Rocks preserved in the Mojave Desert Province collectively record a rich assemblage of Precambrian crystalline basement ranging in age from ca. 1.8 to 1.35 Ga, upper Precambrian and Paleozoic Cordilleran miogeoclinal sediments and platform rocks, Mesozoic backarc and interarc shallow marine and continental sequences, locally emplaced Permian-Triassic syenitic plutons, extruded hypabyssal volcanic rocks of the ?Jurassic "Sidewinder Volcanic Series," and regionally intruded late Mesozoic granitoid batholithic rocks (Dokka et al., 1988).

The Mojave block apparently was a high-standing element for much of the early Tertiary, with strata of Late Cretaceous or early Tertiary age preserved only on its margins.

Beginning about in the late Oligocene an intense episode of regional north-south extension was developed in a roughly east- west trending belt that traversed the central part of the province. This extensional belt has been termed the Mojave Extensional Belt. The extensional regime lasted from about 22-17 Ma, and is generally divided into two phases. The first, from about 22-20 Ma records intense extension via the activity of crustal-scale, simple shear, low-angle normal faults, high-angle normal faults, and extensional fracturing, along with intrusion of intermediate to silicic volcanic rocks, including episodes of explosive volcanic activity. The Peach Springs Tuff, a major regional marker unit that extends across the Mojave from Arizona to about Barstow, forms an effective stratigraphic lid on the extensional interval, (i.e., is not rotated) and is dated isotopically at about 18.5 Ma.

The extensional episode was followed by an interval of high- angle normal faulting and dike emplacement from about 19 to 17 Ma, and was accompanied by at least local uplift and volcanism. Most volcanoclastic and epiclastic sedimentary units of the central Mojave block post-date the interval of extension and normal faulting, and occur as a complex of marginal alluvial and more interior lacustrine facies that formed as recently as late Miocene (ca 13 Ma). Local sequences (e.g., Lava Mountains) record deposition up to about 8 Ma, but there appears to be a regional "gap" from then until at least local successions record Pleistocene deposition. Magnetic and isotopic age studies indicate a complex history of crustal rotations, distributed across a number of discrete domains, during the past 10 Ma. Some of the youngest volcanic and geomorphic features apparently developed at "holes" formed at the edges of rotated blocks.

## INTRODUCTION

This report focuses on the Cenozoic geology and developmental history of the Mojave Desert Province, as reflecting the present author's main temporal and spatial experience in this part of North America. Overall, the Mojave Desert Province is embraced within an area of about 15,000 miles square (19,760 km sq.) that is bounded on the southwest by elements of the San Andreas fault; on the north and northwest by the Garlock fault; and on the east by the Death Valley-Granite Moun-

tains fault zone (Figures 1 and 2). Geomorphologically, the province is comprised of a number of isolated mountain ranges having elevations of about 2,000 - 3,000 feet (600-900 m), separated by tracts of alluvial cover. In many cases, alluvial fans which formed as recently as late Pleistocene are now being incised, encouraged by continued regional uplift even in spite of the generally more arid climate of the past 11,000 years. Some of the obviously geomorphically young lava flows and present playa lakes originated within the last 11,000 years.

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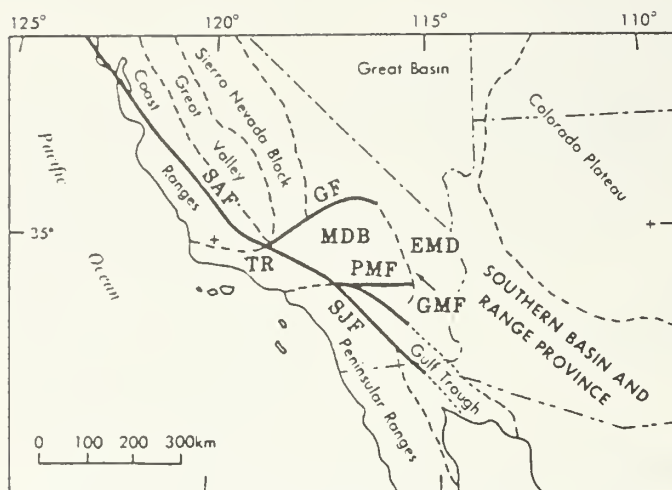


Figure 1. Index map of the Mojave Desert Province region. MDB = Mojave Desert Province; EMD = Eastern Mojave Desert; GMF = Granite Mountains fault; SAF = San Andreas fault; GF = Garlock fault; PMF = Pinto Mountain fault; TR = Transverse Ranges; SJF = San Jacinto fault. From Dokka *et al.* (1991).

Although considered a province, the Mojave Desert region is cut by a large number of northwest-trending faults that have a general sense of right lateral displacement, and a smaller number of faults that trend about east-west and are considered to show left-lateral offset. Especially in the central area, between the Mud Hills and Gravel Hills on the west and the Cady Mountains on the east, the strata were subsequently deformed, folded, and cut by faults that either trend northwest and show right-lateral separation or trend about east west and show left-lateral separation.

A model of crustal rotation for greater southern California originally proposed by Kamerling and Luyendyk (1979) and Luyendyk *et al.* (1980) suggested that crustal blocks in this area that are bounded by east-west trending faults experienced ca 90° of clockwise rotation during the Miocene. Blocks bounded by northwest-trending faults were considered to have undergone no significant rotation (see examples of such blocks in Figure 6). Further work indicated a much more complex history of crustal activity, however, with the amount, sense, and timing of rotation depending largely on whether the terrane under consideration was west of both the San Gabriel and San Andreas faults, between those faults or east of the San Andreas fault (e.g., Hornafius *et al.*, 1986; Golombeck and Brown, 1988; Carter *et al.*, 1987).

Weldon (1985) has suggested that rocks of the Crowder Formation and younger strata as well in Cajon Valley have undergone no significant rotation since their deposition beginning about 17 Ma. This implies that the adjacent parts of Cajon Valley and the San Bernardino Mountains have undergone no rotation, as well.

MacFadden *et al.* (1990a) analyzed the paleomagnetic properties of the type Barstow Formation in the Mu Hills (Barstow Syncline; Figure 2), and suggested that this unit (and hence the district in which it lies) has undergone negligible rotation since its deposition, ca 1 Ma. In conformity with the Kamerling and Luyendyk (1979) model, this area is bounded by northwest striking faults.

MacFadden *et al.* (1990b) also analyzed the paleomagnetic signatures of the Hector Formation in the northern Cady Mountains and suggested that these rocks underwent about 26° of clockwise rotation subsequent to their deposition, or after about 16 Ma. Also consistent with the general model, the Cady Mountains fault that bounds the Hector rocks on the south displays left-lateral separation.

In other studies, Ross *et al.* (1989) suggest that number of terranes in the central Mojave Desert associated with northwest trending faults underwent about 30 to 50° of clockwise rotation post-early Miocene, in some places subsequent to about 50° + 15.6° of clockwise rotation during the time of early Miocene extension.

Among the interesting aspects of the scenario of deformation across the Mojave Desert is whether or not deformed homogeneously by simple shear (e.g., Garfunkel, 1974), whether the rotation was mostly counterclockwise (e.g., Garfunkel, 1974), or otherwise, and whether or not the rotation(s) took place mostly in the late Miocene (e.g., Kamerling and Luyendyk, 1979).

It is well known that both right-lateral and left-lateral families of faults on the Mojave Desert have been active into Recent or nearly Recent times (such faults include the Cady fault and the faults that cut the Mud Hills area; see Figure 3). Meisling and Weldon (1989) indicate that tectonic activity in the San Bernardino Mountains associated with northwest-trending faults along its northern front began between ca 1.5 Ma and 0.7 Ma, and activity continues to the present.

Regional studies also link the onset of the most recent phase of activity along the San Andreas fault with the time of opening of the Gulf of California (e.g., Atwater, 1970). In this context it is relevant that Dokka and Travis (1990a, b) suggest that as much as 65 km of cumulative right shear is distributed across several domains that embrace the Mojave Desert block; that each domain has accommodated the strain independently of the others (some hardly rotated or faulted at all; e.g., the Antelope Valley; Figure 12); that virtually none are physically linked to the Garlock fault, and that all domains experiencing activity did so sometime in the past 10 Ma, but more likely that the deformation began considerably more recently than the

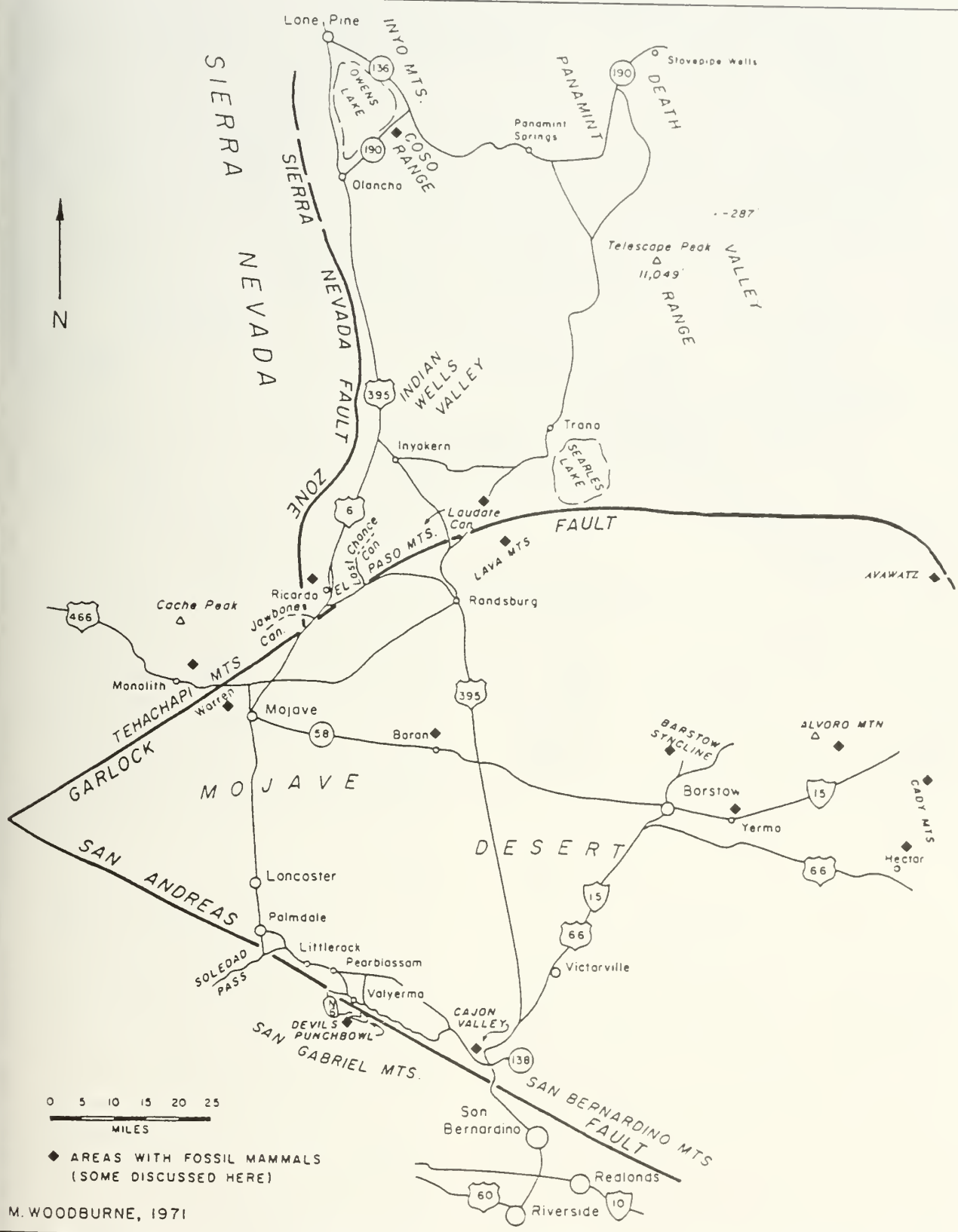


Figure 2. General map of the greater Mojave Desert, from Woodburne (1971).

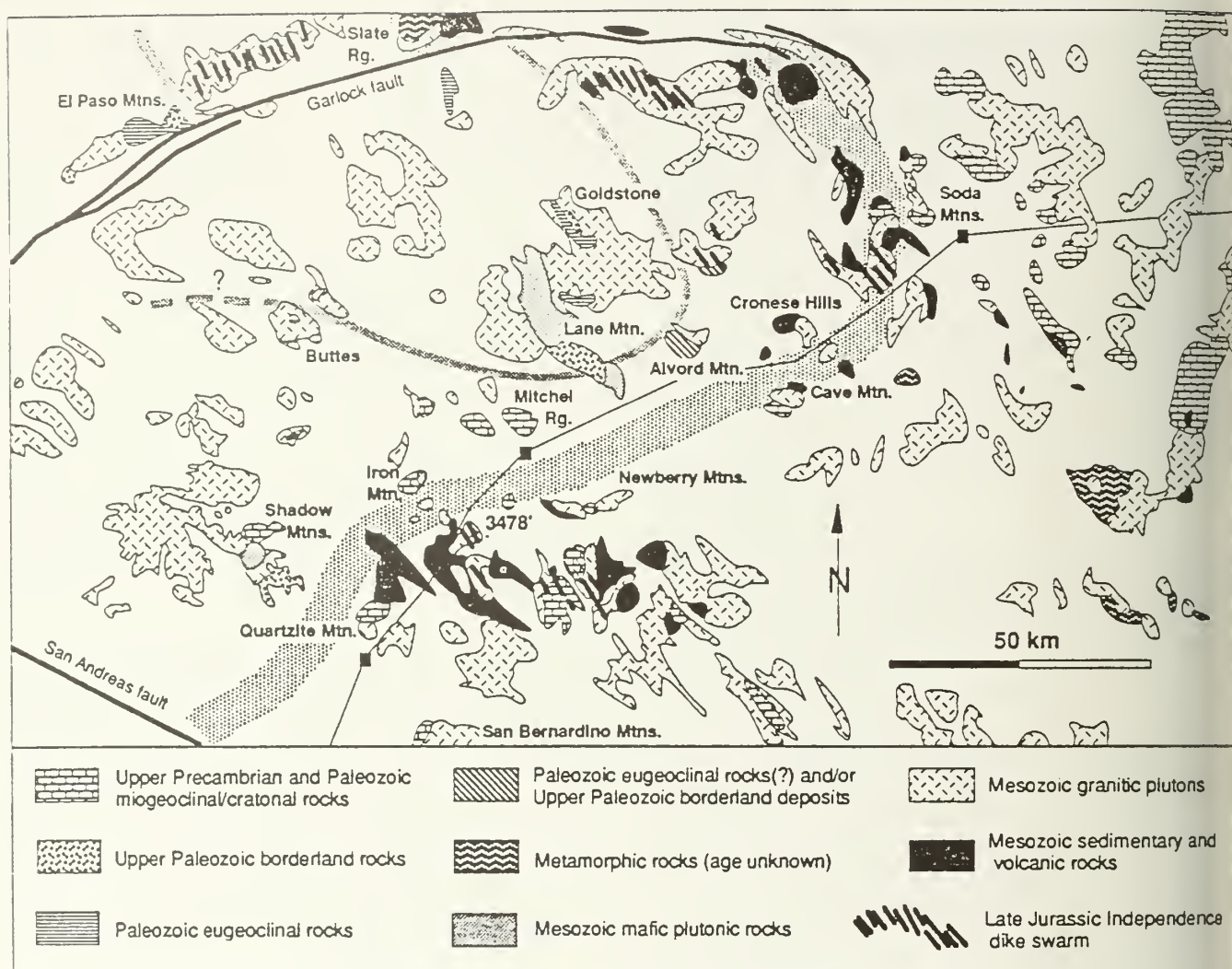


Figure 3. Late Precambrian and Paleozoic geology of the Mojave Desert Province. After Martin and Walker (1991; Figure 5).

Numerous additional observations on recency of faulting (including the Landers and Big Bear, California, earthquakes of 1992 —Jaume and Skykes, 1992; Stein et al., 1992; Sieh et al., 1993) show that the fault complexes of the Mojave Desert Province still are active, and in the senses predicted by their orientations. The fault activity associated with the Landers events is considered by Sieh et al. (1993) to have occurred on elements of the Eastern California Shear Zone, recently proposed by Dokka and Travis (1990a, b). Thus, under the models proposed above, and others cited below, the Mojave Desert Province still must be tectonically active, and still undergoing crustal rotations and other displacements. At the very least, the Mojave Desert Province would appear to be a very unsuitable candidate for locating toxic waste or other disposal facilities that depend upon geologic quiescence!

## PRE-TERTIARY RECORD

The following is designed to survey main pre-Tertiary phenomena and rock suites in the Mojave Desert Province so as to set the stage for the Tertiary events that are important to the present-day geomorphology and distribution of economic resources.

### Precambrian and Paleozoic

The Archaean record of the Mojave Desert Province is virtually nonexistent. Martin and Walker (1992) present evidence that elements of Proterozoic basement rocks ranging in age from about 1.8 to 1.35 Ga are exposed in a small number of places in the central and western Mojave Desert Province (Figure 3), and suggest that the basement (quartzofeldspathic augen gneiss) and associated



metasedimentary rocks correlated with Paleozoic geoclinal and cratonal strata continue uninterrupted west-southwest from the Death Valley area, across the Mojave Desert Province, to the San Andreas fault.

Stewart (1991) summarizes data from western North America to show that, on a regional basis, crystalline basement (1.4-2.5 Ga) was developed approximately cointerval with the augen gneisses discussed above. Apparently, on the other hand, a suite of supracrustal rocks (at Supergroup and analogs) ca 1.5-0.8 Ga in age, and the Proterozoic diamictite and volcanic suite (ca 0.770-0.650 Ga) are lacking in the Mojave Desert Province. As the latest Proterozoic and Paleozoic succession discussed below apparently rests with profound unconformity upon augen-gneiss crystalline basement.

The best exposures of late Proterozoic to Paleozoic strata are found in the northern San Bernardino Mountains, where Brown (1991) records a metasedimentary succession that unconformably overlies basement gneiss and ranges in age from late Proterozoic through Cambrian, with a major unconformity represented by the lack of Ordovician or Silurian strata, and one of lesser magnitude at the base of the Pennsylvanian sequence. The entire succession is metamorphosed, but Brown (1991, Figure 4) records a tectonic thickness of 8,000 m; most units are dominantly carbonate in composition, but the lowermost are siliciclastic. Collectively the strata accumulated in shallow marine environments of the Cordilleran miogeocline, as indicated by the presence of stromatolitic and thin-bedded cryptalgal dolomites. Higher-energy environments in parts of the Devonian and Pennsylvanian strata are reflected in limestones of variable bedding thickness, textures and purity. A number of Mississippian and Pennsylvanian rock units appear to have originated as bioclastic limestones, representative of carbonate bank deposits that formed in high-energy, shallow marine conditions. In contrast to many of the Paleozoic strata of southeastern California, the successions in the San Bernardino Mountains (and also that in the Shadow Mountains to the northwest [Figure 3]) are of Death Valley affinity, rather than being related to successions of the Grand Canyon district.

The base of the metasedimentary sequence (late Proterozoic through Cambrian) begins with a succession of quartzite, phyllite, and marble, known as the Big Bear Group, followed by strata correlated with the late Pre-Cambrian Johnnie Formation and Stirling Quartzite. The latest Precambrian to early Cambrian Wood Canyon Formation (cross-bedded, pebbly quartzite; phyllite and sandstone) is next, followed by the Zabriskie Quartzite. The latter formation records the transition from the siliciclastic to carbonate deposition (calc-silicate rocks, schist, and mafic gneiss, gray laminated siliceous marble with Girvanell-

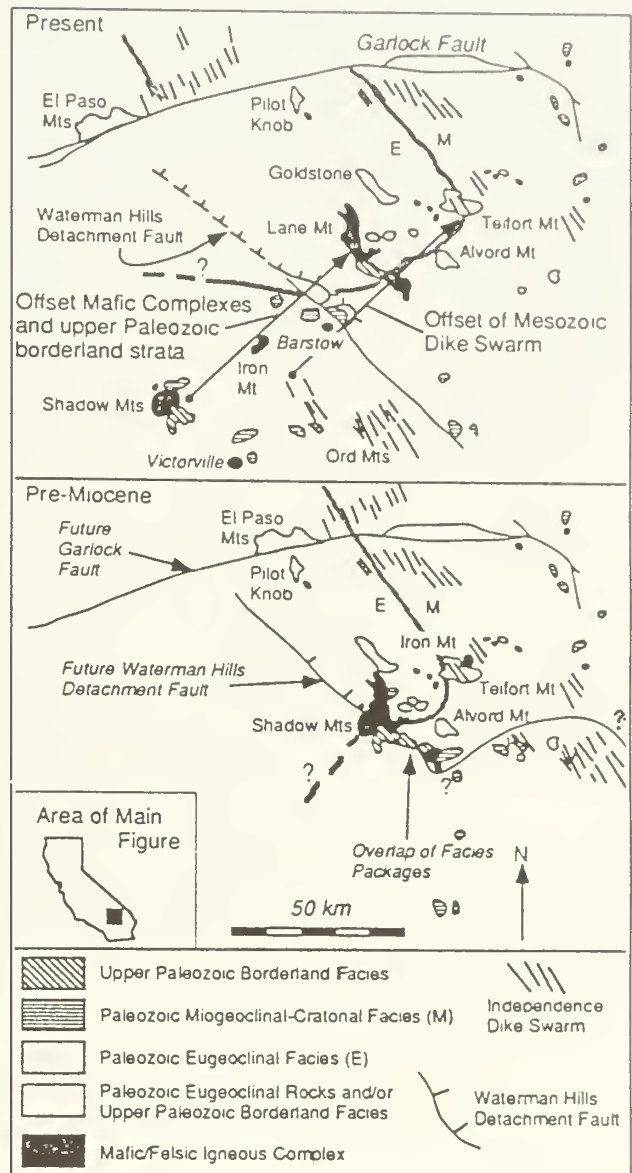


Figure 4. Mesozoic geologic features in the Mojave Desert Province. After Martin and Walker (1991; Figure 6).

la). Fedo and Prave (1991) indicate that some Cambrian units east of the Mojave Desert Province (Tapeats Sandstone, Wood Canyon Formation, Zabriskie Quartzite) accumulated as continental, braided stream, deposits.

The remaining Cambrian through Devonian (but no Ordovician or Silurian) sequence is largely dominated by dolomites, with details of lithology, and calc-silicate and hornfels marker beds allowing the recognition of a number of regionally important lithostratigraphic units at both formation and member scale (oldest to youngest): Bonanza King and Nopah formations (Cambrian) and Sultan Limestone (Devonian, with characteristic stromatoporoids).

The upper Paleozoic strata are comprised of shallow-water carbonate platform sequences. These units, recognized as the Monte Cristo Limestone (Mississippian) and Bird Spring Formation (Pennsylvanian and Permian) are chiefly limestone and marble, with a number of member-scale units also distinguished. Conodonts and corals of Chesterian age have been recovered from the Monte Cristo Limestone; Bird Spring fossils include conodonts of Morrowan age and solitary corals, bryozoans, brachiopods, pelmatozoans, and fusulinids (see Brown, 1991, for more details).

Taken together these sequences reflect deposition in a passive margin tectonic environment (e.g., Sheehan and Boucot, 1991; Martin and Walker, 1992), who also present (Martin and Walker, 1991) a detailed discussion of the upper Precambrian and Paleozoic sequences exposed in isolated places upon the Mojave Desert Province. Martin and Walker (1991) suggest that the pre-Pennsylvanian miogeoclinal-craton hingeline extended southwestward from the Soda Mountains on the northeast toward Quartzite Mountain (Figure 3) in which district neither a fully developed miogeoclinal nor a thin cratonic section was formed. Martin and Walker (1991) explain the general incompleteness of Ordovician and Silurian sequences along this line (and extending into the San Bernardino Mountains, as discussed above) as reflecting the presence of this being the zone of onlap between the miogeocline and the craton. Alternatively, Sheehan and Boucot (1991) cite late Ordovician glacio-eustatic lowering of sea level to account for at least partial elimination of the record in Nevada, to the east, as well as a reconstruction that places California out-board of a deepening continental slope in the early Silurian. Apparently, more data still are needed to reconcile various possibilities to account for the attenuated Ordovician-Silurian record in the Mojave Desert Province.

Martin and Walker (1991, 1992) also summarize evidence for the presence of eugeosynclinal rocks in local exposures in the western Mojave Desert (Figure 3; El Paso Mountains and Goldstone areas). In the Goldstone area, Pilot Knob, and the El Paso Mountains, the eugeosynclinal rocks are characterized as consisting chiefly of calcsilicate hornfels, interbedded orthoquartzite, pelitic schist and phyllite, siliceous argillite, impure chert and limestone, greenstone breccia, metabasalt and andesite. See also Miller and Sutter (1982), who consider the El Paso Mountains and Goldstone sequences to have undergone similar Permo-Triassic southwest-vergent contractile deformation along with greenschist metamorphism, and to be generally correlative. Ordovician graptolites are preserved in the El Paso Mountains sequence, whereas arenaceous limestones of medial and late Devonian age are unconformably overlain by early Mississippian argillite and conglomerate (see also Carr et al., 1984).

Martin and Walker (1991) provide a general, semi-quantitative reconstruction of the Paleozoic geologic setting of the Mojave Desert Province, restoring a number of episodes of post-Paleozoic tectonic deformation. Their reconstruction suggests that facies of Upper Precambrian through Mississippian rocks in the Mojave Desert Province trended south-southwest and that the eugeosynclinal rocks are out of place with respect to the miogeoclinal facies and have been juxtaposed against them by some still unknown process.

### Late Paleozoic and Early Mesozoic.

Martin and Walker (1991) summarize their own data and work by others to document Permo-Triassic deformation in a number of places on the Mojave Desert Province. These can be summarized largely on the basis of the El Paso Mountains succession which is the best developed. There, southwest vergent folds involve eugeosynclinal as well as Pennsylvanian and Permian borderland stratovolcanic rocks of late Permian age and a syntectonic gneissic pluton dated at 249 Ma (zircon; U/Pb; see Carr et al., 1984). Similar relationships that collectively suggest late Paleozoic uplift and erosion prior to the deposition of Triassic strata are found in the Goldstone area, Quartzite Mountain, and Soda Mountains. Along with the juxtaposition of eugeosynclinal and miogeoclinal facies (above), the data suggest to Stevens and Stone (1988) and Walker (1988) that the continental borderland underwent transpressional reorganization during the late Permian such that the previously north to northeast trending continental margin now trended northwest. Their data are somewhat ambiguous however, so that Snodgrass (1990) postulates an alternative suggestion that the sequence accumulated in a contractile setting associated with late Paleozoic thrusting.

### Mesozoic

Probably the most impressive aspect of the Mesozoic history of the Mojave Desert Province is the widespread, nominally Cretaceous, plutonism of general granodioritic composition. Other evidence, however, indicates that the Mojave Desert Province was a positive feature undergoing a variety of tectonic events throughout the Mesozoic.

Geologic events during the Mesozoic Era include the deposition of the Fairview Valley Formation northeast of Victorville (Figure 4) and related areas (Lane Mountain, Figure 4): calcsilicate metasiltite and conglomeratic marble (Martin and Walker, 1991) of early Triassic age. These strata unconformably overlie older rocks (= Triassic overlap sequence of Burchfiel et al., 1980; Walker, 1988). Other units of significance include the Sidewinder Volcanic "Series" of Dibblee (1967) of early to medial Jurassic age (174-166 Ma; Busby-Spera, 1988) and possibly representing an extensional arc setting that now trends about



est-west between Victorville and Barstow. This regime apparently was superseded by a belt of contractional (formation, represented in part in the Cronese Hills ca 9-154 Ma (Walker et al., 1990). The Cronese Hills data may be part of a regional episode of contractile deformation (e.g., the eastern Sierra thrust system of Dunne, 1986, and references cited therein). Martin and Walker (1991) thus portray a belt of medial to late Jurassic contractional formation that extends southeastward from the Soda Mountains to the San Andreas fault via the vicinity of Quartzite Mountain (Figure 3) to underscore this relationship.

The Independence Dike Swarm (and apparently coeval dikes of late Jurassic age (ca 148 Ma; e.g., James, 1989) in the Tiefort Mountains and Ord Mountains represents a major piercing point for reconstructions of tectonic events across the Mojave Desert Province (Martin and Walker, 1991). Assuming that the various elements of the "dike swarm" were originally aligned, their present locations suggest about 50-60 km post-Miocene right-lateral slip on the Garlock fault and an apparently similar magnitude of right-lateral offset along a presently undiscovered fault that extended northeastward (present day directions) toward, but passed south of Alvord Mountain (Figure 4).

Finally, a number of authors (see Martin and Walker, 1992) has postulated the presence of a major right-lateral fault (ca 400 km slip) of about early Cretaceous age extending across the western Mojave Desert Province in order to link late Precambrian to Paleozoic strata in the San Bernardino Mountains and Quartzite Mountain, as well as pre-Triassic unconformities and Independence age dikes with beds and structural relationships now preserved in the Snow Lake area in northern Yosemite National Park. Martin and Walker (1992) develop data to suggest that this fault, if present, must occur west of the Shadow Mountains (Figure 3). The fault is considered (Lahren et al., 1990) to have been active between 148 and 110 Ma, but evidence for this structure in the Mojave Desert Province is limited (Martin and Walker, 1991).

## THE MOJAVE DESERT PROVINCE

### Cenozoic

The Mojave Desert Province (MDB, Figure 1) as we know it came into existence in later Cenozoic time, when the bounding faults that now define it were activated, and when the main geologic episodes that characterize it transpired.

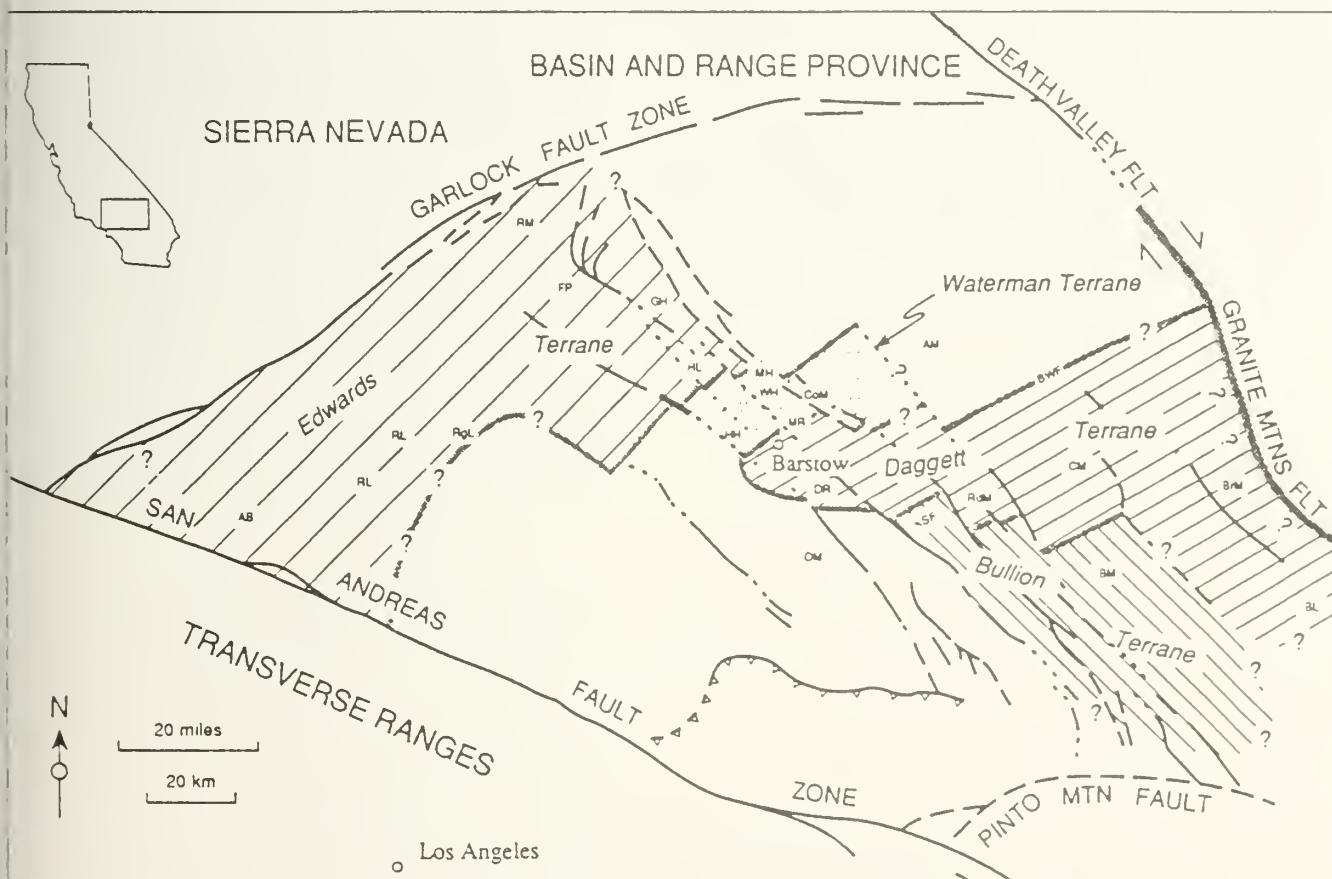


Figure 5. Mojave Extensional Belt. After Dokka et al. (1991).



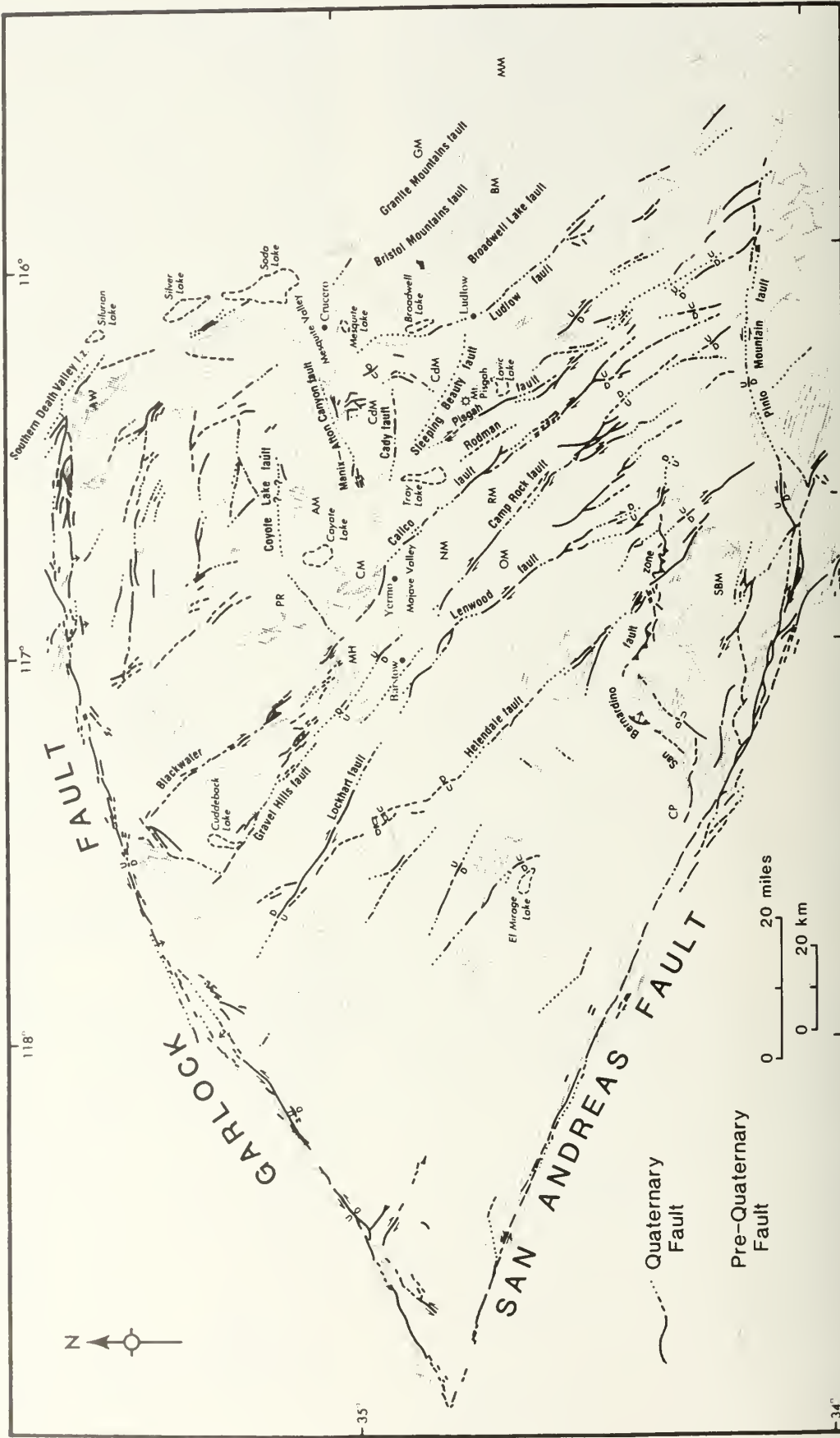


Figure 6. General fault map of the Mojave Desert Province. After Dokka et al. (1991).

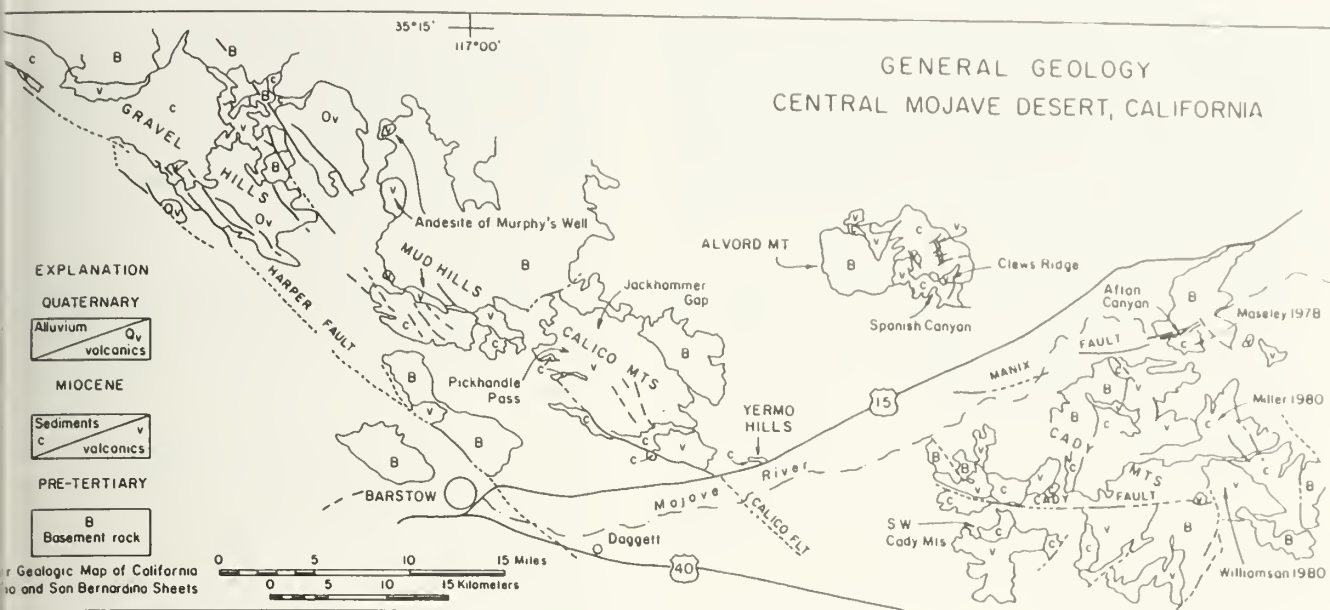


Figure 7. General geology of the central Mojave Desert. From Woodburne (1991).

Hewett (1954) was one of an early generation of geologists interested in the geological history of the Mojave Desert Province to suggest that it must have been a high-standing terrane for much of the early part of the Cenozoic. Indirect evidence of this is recorded on the northern and southwestern margins of the province. Cox (1937) has shown that the Paleocene to Eocene (McKenzie et al., 1987; McDougall, 1987) Goler Formation of the Paso Mountains was deposited in part by streams flowing about westward from the Mojave Desert Province across the present trace of the Garlock fault, and Kooser (1930) and references cited therein indicate that the San Jacinto Formation of Late Cretaceous to possibly Paleocene age accumulated in marine borderland basins adjacent to the Mojave on its southwestern margin. Byers (1950), among others, notes the presence of an undated unit with a few meters in thickness that is developed on Tertiary basement and overlain by the oldest (nominal) late Oligocene or early Miocene in present terminology. Nonmarine deposits formed upon the Mojave Desert Province, itself.

Beginning in about the late Oligocene, an intense episode of regional north-south extension was developed as a roughly east-west belt that traversed the central part of the Mojave Desert Province. This has been termed the Mojave Extensional Belt (e.g., Dokka, 1986; Dokka, 1989; Dokka et al., 1988; 1991). As discussed in Dokka et al. (1991), the belt (Figure 5) is comprised of four domains (wards, Waterman, Daggett, and Bullion terranes). A terrane consists of one or more half-grabens; the half-graben contains blocks of tilted rock that are bounded by normal faults and overlies a rooted detachment fault.

Differential extension between the domains was accommodated by transfer zones comprised of strike-slip faults, and regional kinematic indicators suggest to Dokka (1989) that the western part of the extensional belt opened in a NE-SW direction, in contrast to eastern part opening in a ENE-WSW direction. Paleomagnetic data (Golombek and Brown, 1988; Ross et al., 1989) indicate that the region has been rotated about 50° (clockwise) between about 20 and 18 Ma, so that the overall direction of extension of the belt originally was directed about N-S. Ross et al. (1991) report on changes in declination vectors contained in a Miocene succession in the western Cady Mountains that demonstrate the rotation episode to post-date the detachment faulting. See Figure 6 for a general fault map of the Mojave Desert Province.

The extensional regime lasted from about 22-17 m.y. and is generally divided into two phases. The first, from about 22-20 m.y. records intense extension via the activity of crustal-scale, simple shear, low-angle normal faults, high-angle normal faults and extension fracturing along with intrusion of intermediate to silicic volcanic rocks, including episodes of explosive volcanic activity (e.g., Pickhandle Formation in the Mud Hills and Calico Mountains, and the Spanish Canyon Formation of Alvord Mountain. The Peach Springs Tuff, a major regional marker unit that extends across the Mojave from Arizona to about Barstow, forms an effective stratigraphic lid on the extension interval, and is dated isotopically at about  $18.5 \pm 0.2$  Ma (Nielson et al., 1990). This extension episode was followed by an interval of high-angle normal faulting and dike emplacement from about 19 to 17 Ma.

The extension interval was accompanied by at least local uplift, with the Waterman Gneiss, in the Waterman Hills south of the Mud Hills which contain the type Barstow Formation, having risen about 20-30 km during this time (e.g., Dokka, et al., 1988). Beginning about 16 Ma clasts of Waterman Gneiss are contained in type Barstow Formation sediments on the south side of the Mud Hills (e.g. Woodburne et al., 1990).

Figures 2 and 7 show the distribution of most of the areas on the Mojave Desert that yield stratigraphic sequences important for this discussion. Dokka et al. (1991) point out that uplifts in the Harper Lake and Mitchell Range areas separated the Mojave Extensional Belt into two major basins, dubbed the Boron and Barstow. Of these, the Barstow has the more complete stratigraphic record. Also shown are sequences adjacent to the Mojave Desert Province, in that they record information useful to reconstruction of events thereupon. Woodburne (1991; See Figure 8) summarizes much of the nonmarine stratigraphy that is relevant to this report, but see also Dibblee (1967), Woodburne et al. (1982), Whistler (1984), and Whistler and Burbank (1991).

Some rock units (Jackhammer Formation, "Formation of Lead Mountain," Lane Mountain Quartz Latite, pre-Hector Formation andesites, andesitic basalts, rhyodacitic flows, breccias, etc., apparently accumulated in an interval of from possibly as old as 30 Ma to about 23 Ma, prior to the main interval of extension.

The main extensional interval, from about 22 - 20 Ma, is represented by the lower parts of the Hector and type Barstow formations, the lower units that crop out in the Alvord Mountain (Clews Fonglomerate, Alvord Peak Basalt; Spanish Canyon Formation), and in the Calico Mountains-Lead Mountain district syntectonic conglomerate and breccia). Comparable units also occur in the Rodman and Newberry Mountains and in Daggett Ridge.

Most volcanoclastic and epiclastic sedimentary units of the central Mojave block post-date the interval of extension and normal faulting, including units that occur as a complex of marginal alluvial and more interior lacustrine facies that formed as from about 19 - 13 Ma. These deposits, generally termed Barstow Formation or equivalent, contain numerous beds of air-fall and water-laid tuff that form convenient marker beds as well as being amenable to isotopic age analysis. The rocks are also locally fossiliferous, as well, and contain the main record of fossil mammal evolution in the Mojave Desert Province.

The following discussion begins with a summary of the Cenozoic geology of Cajon Valley, an important area just beyond the present borders of the southwestern edge of the Mojave Desert Province, and then continues with other districts on, or just adjacent to the northern borders of the province.

## Cajon Valley

Cajon Valley (Figure 2) is rising at an average rate of about 19 inches/100 years (Gilluly, 1970). In a million years, and if there were no concurrent or subsequent erosion, this could give rise to a mountain range 20,000 feet (6,076 m) tall. The area was at or near sea level at times in the past, however.

Now truncated on the southwest by elements of the San Andreas fault system, strata in Cajon Valley (Figure 8) record at least two intervals of marine encroachment (San Francisquito(?) and Vaqueros (?) formations; Late Cretaceous to Paleocene and late Oligocene-early Miocene, respectively), followed in the medial Miocene by broad-scale nonmarine deposition (Cajon Valley beds and Crowder Formation) by streams flowing toward the southwest and south from the adjacent Mojave Desert block. Fossil mammals of late Hemingfordian to late Barstovian (Cajon Valley beds) and late Hemingfordian to Clarendonian age (Crowder formation) have been recovered in these deposits (e.g., Woodburne and Golz, 1972), Reynolds (1985).

The area also was tectonically active in the medial Miocene, with uplift west of the Cajon Valley fault supplying debris into the Cajon Valley beds, as shown by the clastic wedge (CW) on Figure 8. Sometime between 9 and 4 m.y., the Squaw Peak thrust juxtaposed the on-separate Crowder and Cajon Valley basins. Meisling and Weldon (1989) suggest that the Crowder basin was originally located to the northeast or east of Cajon Valley, and was translated to its present position.

Deformation along the Squaw Peak fault (Foster, 1980, 1982), apparently coincided with a depositional hiatus, but was finished at least by about 4 Ma, when the Phelan Peak deposits of Meisling and Weldon (1989) accumulated across its trace, still derived in part from a Mojave Desert source (Figure 8).

This unit was followed at about 1.6 Ma by the relatively fine-grained Harold Formation whose ages are about equivalent to the Irvingtonian here (based on magnetic stratigraphy and fission-track data; Meisling and Weldon, 1989) but, in its type area near Palmdale, is of Rancholabrean age based on fossil mammals (e.g., Noble, 1953; Dibblee, 1967; Woodburne and Golz, 1975; Woodburne, 1975).

The Harold Formation and the overlying Shoemaker Gravel (also of about Irvingtonian-equivalent age here) contrast to its fossil-based Rancholabrean age in its type area to the northwest; Noble, 1954a) record the first major input of clastic materials from sources southwest of the San Andreas fault system (e.g., Sharp and Silber, 1971; Woodburne, 1975; Meisling and Weldon, 1989), and show that the San Gabriel Mountains were a high-



ding range at this time and shedding debris north- as they passed by the Cajon Valley area. Although Phelan Peak deposits are viewed as being transitional in regard, the Harold and Shoemaker units herald the beginning of the modern-day drainage regime. Drainage streams, such as the Mojave River, flow north- from the Transverse Ranges, rather than the prevail- south to southwesterly flow of streams that prevailed in this area from at least the Late Cretaceous, and which modern Cajon Creek is trying to re-establish.

## Central Mojave Desert

Figures 7 and 8 show the districts in the central Mojave Desert having sequences useful to fossil mammal stratigraphic and faunal analysis, and thus fundamental control, locally augmented by radioisotopic and geochronostratigraphic information. Some of these areas contain unfossiliferous rock sequences that pertain to extensional episodes that affected this area, as well.

As indicated in the introduction, a diverse basement terrane in the central Mojave Desert is overlain unconformably by a thick sequence of Tertiary-age volcanic and epiclastic sediments interbedded with air- and some ash-flow tuffs. The Tertiary rocks range in age from more than 26 Ma to about 12 Ma and record the development of internal drainage in the Mojave Desert Province (Hewett, 1954; Byers, 1960). Lacustrine sediments in the Lead Mountain area south of the Calico Mountains are somewhat older than 26 Ma (see Figure 8), and the Hammer Formation may be about that old, as well. The apparent absence of Upper Cretaceous to lower Tertiary terrigenous strata on the Mojave Desert Province is striking, with the only hints as to local activities during that time provided by units exposed on the north- (Goler Formation; Laudate Canyon, Figure 2) and west- (San Francisquito Formation) margins of the block (Devil's Punchbowl and Soledad Pass area; Figure

Most of the mammal-bearing rock units in the central Mojave are referred to the Barstow and Hector Formations. The Barstow depocenter apparently was confined mostly to the western part of the district, from the Silver Hills to the Alvord Mountains (Figure 7), and ranges in age from about 19-13 Ma. The Hector Formation flanks the Cady Mountains in the eastern part of the district and ranges in age from about 22-16 Ma.

The Avawatz Formation (ca 20-11 Ma old), is exposed in the Avawatz Mts. on the eastern margin of the district. It is one of the youngest Miocene rock unit exposed in this district, and may more properly be considered as related to events on the southern Basin and Range

Province near the southern end of the Death Valley fault zone (e.g., Spencer, 1990a, b). The Avawatz Local Fauna (Henshaw, 1939) is of Clarendonian age and is derived from the upper part of the Formation in association with a tuff dated at ca 11 Ma (e.g., Evernden et al., 1964).

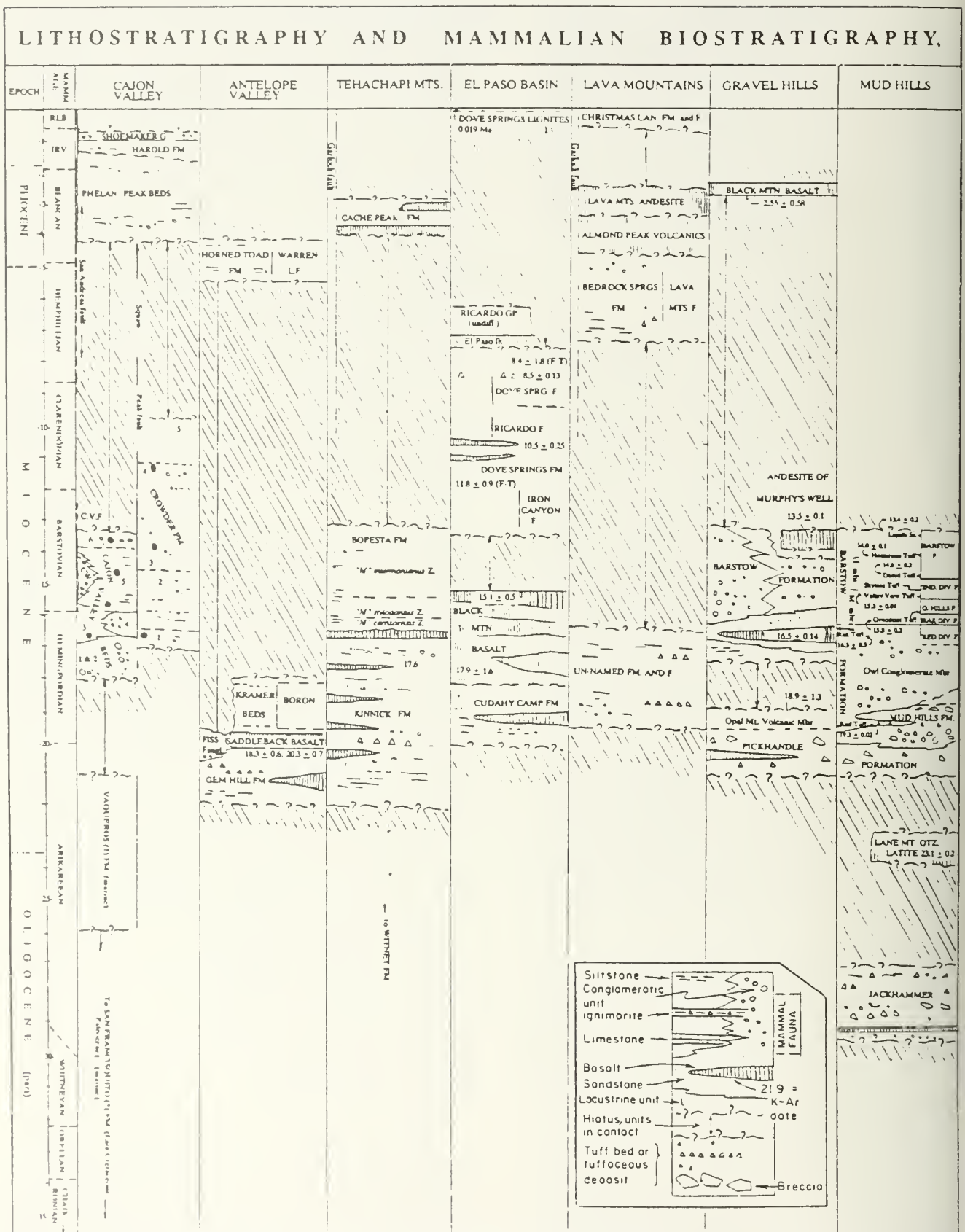
On the northern edge of the province, and south of the Garlock fault, the Bedrock Springs Formation contains fossils of middle to late Hemphillian age (Smith, 1964; Whistler, this report), and is a little younger than the Dove Spring Formation, but may be about as old as sediments assigned to the Ricardo Group (Whistler and Burbank, in press; Whistler, this report), exposed on the north side of the Garlock. The Dove Springs Formation of the Ricardo Group ranges in age from latest Barstovian to early Hemphillian, or from about 12.5 to 7 Ma.

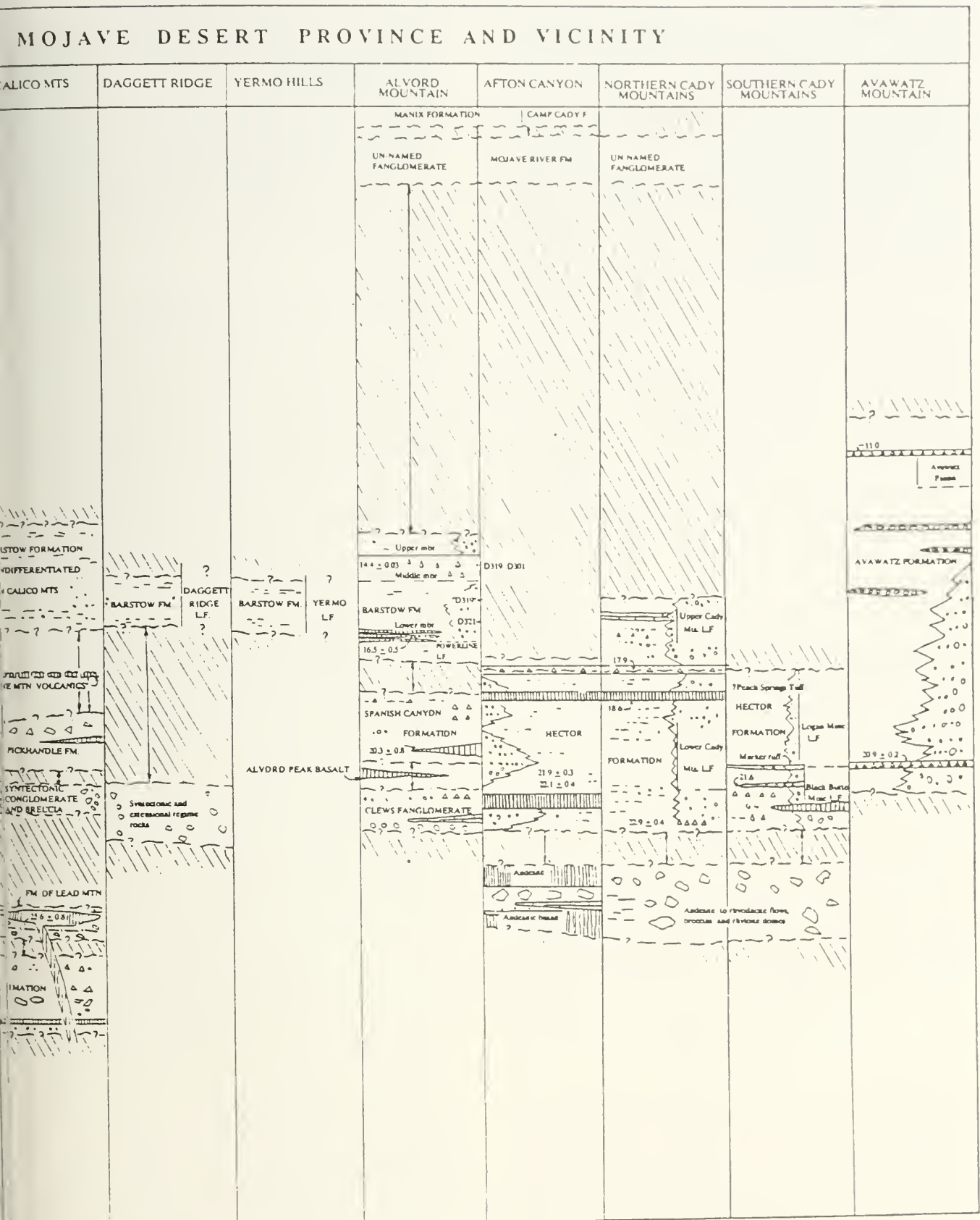
References for the geologic history of the Garlock fault and adjacent areas include Dibblee (1952), Garfunkel (1974), Cummings (1976), Cox (1987), Loomis and Burbank (1988), Pampeyan et al. (1988), Dokka and Travis (1990a, b).

The Tropico Group (vicinity of Boron to Mojave; Figure 2) of Dibblee (1967) includes the Gem Hill Formation, Fiss Fanglomerate, Saddleback Basalt and Kramer beds of the Antelope Valley (Figure 8). Whistler and Burbank (1991) relate the deposits of the Boron Basin (Dokka et al., 1991) to those of the Dove Springs Formation and other elements of the Ricardo Group now preserved adjacent to the Mojave Desert Province northwest of the Garlock fault. The Gem Hill Formation, a combination of tuff breccia, tuff, basalt, and tuffaceous sandstone, occurs stratigraphically below the Saddleback Basalt (dated at about 18.3-20.3 Ma; see Whistler, 1984) considered (Dokka et al., 1991) to pertain to the main extensional regime of this part of the Antelope Valley. The Fiss Fanglomerate unconformably overlies the Gem Hill Formation and contains coarse-grained debris derived from the Bobtail Quartz Latite Member of the Gem Hill.

The Boron Local Fauna (Whistler, 1984) comes from the upper part (Arkose member of the Kramer beds) of the Tropico Group, on the western part of the province. The fauna, of early Hemingfordian age, is contained within borate-bearing sediments mined by U.S. Borax. The sediments rest on the Saddleback Basalt, dated (Armstrong and Higgins, 1973) at  $20.3 \pm 0.7$  Ma and  $18.3 \pm 0.6$  Ma (Kistler, in Whistler, 1984).

Farther to the northwest, near the town of Mojave, and yet on the south side of the Garlock fault, the Horned Toad Formation (Dibblee, 1967) has yielded the Warren Local Fauna (May, 1981) of late Hemphillian age (Figure 8). Dibblee (1967) and May (1981) indicate that the Horned Toad Formation consists of a combination of fluvial conglomerates, sandstones, and lacustrine tuff







and shale beds likely derived from locally high-standing elements of the Tropic Group (Bobtail Quartz Latite Member) to the south and west (May, 1981).

Prior to the elevation of the Tehachapi Mountains (Figure 2), the region was topographically much lower. Cache Peak is part of the Tehachapi Mountains just north of the Garlock fault adjacent to the western part of the Mojave Province. The range contains three major Tertiary units. The oldest, the Witnet Formation, is unfossiliferous but is lithologically similar to, and commonly correlated with, the Goler Formation of the El Paso Mountains (Dibblee, 1967; Cox, 1982, 1987; Cox and Diggles, 1986; also shown to be of marine origin at its uppermost intervals (lower Eocene: McDougall, 1987). The Kinnick Formation (Figure 8) unconformably overlies the Witnet, and contains a hornblende biotite tuff breccia dated by Evernden et al. (1964) at 17.6 Ma. Quinn (1987) revised the Kinnick and the conformably overlying Bopesta Formation. As revised, the Bopesta Formation, consists of a sequence of volcanoclastic, epiclastic, and minor lacustrine strata that ranges in age from late Hemingfordian to late Barstovian (Figure 8). These strata apparently accumulated at or near sea level and certainly not at the nearly 4,000 feet (1,400 m) high elevations at which they now reside.

Many of the units described above are unconformably overlain by unfossiliferous units, and some of these likely are of Pliocene age. The Black Mountain Basalt that unconformably overlies the Barstow Formation in the Gravel Hills (Figure 8) has been dated at about  $2.55 \pm 0.58$  Ma (Burke et al., 1982). Nevertheless, throughout the greater Mojave Desert Province there seems to have been a change in regional deposition such that erosion predominated, in contrast to deposition at the scale recorded for the Miocene. This observation leads to the concept of a 5 million year gap that removes or did not record a stratigraphic record that began about 12-10 Ma and lasted until about 5-2 Ma depending upon the district under consideration. Some sequences (e.g., the Ricardo Group adjacent to the Mojave Desert Province suggest that the province was undergoing erosion and units in the Lava Mountains help fill in some of the gap beginning about 7 Ma. Nevertheless, much of the record of the later Miocene is missing from a great span of the Mojave Desert Province (Figure 8).

Some record of events that took place during this interval is preserved in locally derived deposits in or adjacent to the San Bernardino and San Gabriel mountain ranges. These include the succession in Cajon Valley discussed above, and outcrops of the Old Woman sandstone (e.g., Sadler, 1982) that can be traced along the front of the San Bernardino Mountains (about 40 miles

east of Highway 138, Figure 2). Sequences that are geologically thick, relatively continuous, and temporally extensive that span this gap are rare. Probably the best example is the sequence preserved in the San Timoteo Badlands (Frick, 1921; May and Repenning, 1982) but this is adjacent to, rather than on, the Mojave Block (south of Redlands, Figure 2). Resolution of what was taking place during the "missing 5 million-year gap" remains one of the important desiderata in contributing to our understanding of the geological and biological evolution of the region.

The post-Miocene geologic milieu also saw the early to late Miocene units being tilted, folded, and cut by faults that generally trend northwest and show right-lateral separation and, more rarely, trend east-west and show left-lateral separation (Figure 6). During the later part of this interval (mostly Pleistocene) internal drainage once again produced major areas of lacustrine deposition, now recorded by the Manly and other lakebeds in the southern Death Valley, Tecopa, Soda and Manix basins (see Owens Lake, Searles Lake, and area bounded by Highways 5 and 66, Figure 2). These deposits range in age from about 2 Ma to 19,000 years and locally record mammalian taxa of Irvingtonian to Rancholabrean age (e.g., Jeffers, 1985; Reynolds and Reynolds, 1985).

Models proposed to relate the geological features summarized above to the general tectonic regime of North America include (1) plate margin subduction reflected by the onset of Tertiary volcanism (Atwater, 1970; Lipman et al., 1972; Christiansen and Lipman, 1975; Armstrong and Higgins, 1973), (2) interplate strain reflected in counterclockwise rotation of fault-bounded blocks (Garfunkel, 1974; Cummings, 1976), (3) clockwise rotation of selected fault-bounded blocks (Kamling and Luyendyk, 1979, 1985; Luyendyk et al., 1981, 1985; Terres and Luyendyk, 1985; Carter et al., 1985; Hornafius, 1985; Hornafius et al., 1986; Luyendyk and Hornafius, 1987), and (4) a combination of early Miocene extension and post-extensional deposition followed by post-late Miocene faulting and rotation partitioned across six domains from the San Andreas fault to the Death Valley fault zone (Dokka, 1983, 1986, 1989; Dokka and Glazner, 1982; Dokka and Travis, 1990a, b). Bartley et al. (1990) also suggest that the region has been subjected to north-south contraction (see also Smith, 1991).

The following sets out the basic stratigraphic and geochronologic relationships of Cenozoic rock units in selected districts of the Mojave Desert Province. Special emphasis is given to those sequences that have produced fossil vertebrates. Figure 2 shows the general location of these areas; Figure 7, that of the Central Mojave Desert. The section is followed by a summary of tectonic regimes active during the past 5-10 Ma.

## GRAVEL HILLS

The Gravel Hills (Figures 7 and 8), about 35 km northeast of Barstow, record what apparently was the western-most extent of the Barstow and Pickhandle formations. According to Dibblee (1968), the Cenozoic sequence begins with the Pickhandle Formation (V on Figure 8). This largely pyroclastic unit is about 600 m thick, and unconformably overlies pre-Tertiary quartz monzonite. The Pickhandle is mostly composed of light gray breccia and tuff, interbedded with minor basalt flows, conglomeratic lenses, rhyolitic flow breccia, and beds of white lithic and lapilli tuff. Burke et al. (1982) report a whole-rock date of  $18.9 \pm 1.3$  Ma from the Opal Mountain volcanic member at the top of the Pickhandle (formerly considered as a separate unit by Dibblee, 1968).

Dibblee (1968) considered the Pickhandle to have been derived from volcanic centers in the Gravel Hills and in the Opal Mountain area, as well as from loci in the Chico Mountains (vicinity of Pickhandle Pass, Figure 7), and Byers (1960) proposed that the Spanish Canyon Formation of Alvord Mountain, some 60 km to the east, was genetically related to the Pickhandle, as well (see Figures 3 and 4). In the Mud Hills the Pickhandle is exposed mostly on the northern side of the Barstow Syncline, but underlies and interfingers with the Barstow Formation there. Walker et al. (1990) have correlated the top of the Waterman Hills and the Mitchell Range with the Pickhandle, but the great diversity of exotic clasts (apparently derived from the Alvord Mountains) is unusual for the Pickhandle rocks of the Mud Hills (see Mud Hills Formation of Travis and Dokka in Dokka et al., 1991).

The Barstow Formation (C, Figure 7) is more widely exposed in the central and western parts of the Gravel Hills than in the east. It consists of a lacustrine sequence overlain (Figure 8) by basal beds of coarse-grained, friable sandstone and thick units of fanglomerate that contain granitic and volcanic detritus (Dibblee, 1968; pl. 130-31). The total sequence ranges up to 1,500 m in thickness. The basalt flow in Black Canyon near the central Gravel Hills is undated and may not be the same as the one from which Burke et al. (1982) obtained a  $^{40}\text{Ar}$  date of  $16.5 \pm 0.4$  Ma.

Fossil mammals are sparse in the Barstow deposits below the basalt in Black Canyon, but seem to pertain to the Green Hills Fauna of the Mud Hills (Woodburne et al., 1990, Figure 6), calibrated there at between 15.4-15.8 Ma. Those above the basalt in Black Canyon appear to correlate with elements of the Barstow Fauna of the Mud Hills (ca 14.8-13.4 Ma). The mammal remains are fragmentary, and geochronological correlations based on them remain tentative (see also Lewis, 1968b, p. 35).

The two fanglomeratic facies - granitic on the west and southwest, volcanic debris on the north (Figure 8) - reflect deposition from two different sources. Dibblee (1968: 32) suggests that the fanglomerate of granitic and quartz latite clasts were derived from rising basement terranes to the west and southwest; the fanglomerate of volcanic debris apparently accumulated at the same time, but from northwestern sources. These data suggest that the western edge of the Barstow depositional basin lay in the vicinity of the Gravel Hills. Although coarse-grained sediments occur in the western Mud Hills (and generally interfinger eastward with finer-grained units), there is no physical continuity between the Gravel and Mud hills.

The youngest unit of Miocene age in the Gravel Hills area is the "Lane Mountain Andesite" mapped by Dibblee (1968, p. 1) in the vicinity of Murphy's Well (Figure 7) about 10 km north of the western end of the Mud Hills. This unit is shown on Figure 8 as the Andesite of Murphy's Well, dated by Burke et al. (1982) at  $13.5 \pm 0.1$  Ma and, except for resting unconformably on pre-Tertiary basement, is stratigraphically unconfined. Nevertheless, Woodburne et al. (1990) note the presence of a distinctive facies of hornblende-bearing sandstone in the uppermost part of the Barstow Formation in the northwestern Mud Hills, and point out that the age of this part of the formation (ca 13.4 Ma) is very close to the age of the Murphy's Well andesite.

The Black Mountain Basalt, dated at  $2.55 \pm 0.58$  Ma by Burke et al. (1982), caps the Barstow Formation in the Gravel Hills and is an important marker that demonstrates subsequent activity on northwest-trending faults (Harper fault; Figure 7) in this area.

Burke et al. (1982) and Valentine et al. (1988) investigated the possibility of tectonic rotation (about vertical axes) of late Cenozoic units in this area. They suggested that the Opal Mountain member of the Pickhandle Formation and the Andesite of Murphy's Well may have experienced up to  $30^\circ$  of subsequent counterclockwise rotation, but that the Barstow Formation and the Black Mountain Basalt were effectively un-rotated. Note, however, that these possibilities are based on very few data points and must remain tentative.

## MUD HILLS

A relatively complete sequence of deposits of early and medial Miocene age crops out in the Mud Hills, north of Barstow, California (Figures 2 and 7). The sequence consists of the Jackhammer, Pickhandle, and Barstow formations, in ascending order (Figure 8), and the Lane Mountain Quartz Latite (e.g., Woodburne and Tedford, 1982). For geological literature, see also Hershey (1902), Baker (1911), Dibblee (1968), Durrell (1953), Steinen (1966), and Sheppard and Gude (1969). Paleontological



references include Lindsay (1972), Merriam (1913, 1915, 1919), Hall (1930), Stirton (1930), Wood (1936), Stock (1937), Schultz and Falkenbach (1947, 1949) and Tedford and Alf (1962).

The type locality of the Jackhammer Formation is in Jackhammer Gap (Figure 7), in the northwestern Calico Mountains (McCulloh, 1954, in Dibblee, 1968), but the unit is preserved in its western-most occurrence on the north limb of the Barstow Syncline in the Mud Hills (Dibblee, 1968, pls. 1, 3). There the Jackhammer unconformably overlies pre-Tertiary quartz monzonite, is about 30 m thick, and is unconformably overlain by the Pickhandle Formation. In the Calico Mountains, the Jackhammer is about 240 m thick and includes beds of conglomerate, basalt, tuff, tuff breccia and tuffaceous sandstone.

The Jackhammer apparently was one of the earliest units to be deposited in a basin that extended from the Calico Mountains toward the Gravel Hills. In the Calico Mountains area, Lambert (1987) reports that the Jackhammer is cut by dikes dated at  $25.6 \pm 0.8$  Ma. The lower limit to the age of the formation still is unknown but, if Cenozoic deposition on the Mojave Desert is related regionally to the time of beginning consumption of the subduction zone along the western margin of California (e.g., Atwater, 1970), the Pickhandle may not be older than 30 Ma.

The Lane Mountain Quartz Latite is of limited areal extent as restricted by Burke et al. (1982) and dated at  $23.1 \pm 0.2$  Ma. In contrast to Dibblee (1968) who considered the unit to post-date the Barstow Formation, these authors suggest that this quartz latite is a remnant of a number of welded quartz latite ash-flow sheets that locally contain unwelded tuff and vitrophyre at the base. The present areal restriction of this unit suggests considerable erosion subsequent to its extrusion; it also may mark the age of change from a regime that produced mainly andesitic to rhyodacitic extrusive rocks to one that resulted in largely basaltic eruptions and concurrent fluvio-lacustrine deposition and the development (sometimes explosive) of air-fall to ash flow tuffs. Based on data in the Calico Mts. (below), the Lane Mountain Quartz Latite is younger than the Jackhammer Formation and older than the Pickhandle.

The Pickhandle Formation crops out mostly on the north limb of the Barstow Syncline and is there about 1,300 m thick. It is composed of a basal interval of gray conglomerate, and greenish-gray to reddish-gray arkosic to tuffaceous sandstone; this is followed by a middle unit of lithic tuff and andesitic tuff breccia, then succeeded by an upper unit of granitic and rhyolitic breccia and megaconglomerate that is interbedded with the Barstow Formation (Woodburne et al., 1990).

The age of the Pickhandle in the Mud Hills is as late as young as the basal part of the Mud Hills Formation with which it interfingers (below). If the proposed correlation of the Pickhandle and the Spanish Canyon Formation at Alvord Mountain is valid, then the age shown in Figure 8 may be reasonable.

The tuffaceous portions of the Pickhandle apparently were the result of episodes of explosive volcanic activity and the spectacular, thick lenses of monolithologic granitic and rhyolitic breccia exposed in the upper part of the Pickhandle Formation in Owl Canyon may have been deposited as landslides or debris flows. The size of the blocks suggests near-by rather than more distant provenance, and the fact that these overlie tuffaceous units of volcanic origin suggests that the breccias were the result of local tectonic activity that produced a rugged terrain of granitic mountains on the margin of the Pickhandle and, later, the Barstow basin (Dibblee, 1968, p. 22, 23).

Travis and Dokka (in Dokka et al., 1991) remove the breccias and megaconglomerates of Dibblee's (1968) Pickhandle Formation, and term these the Mud Hills Formation. The Mud Hills Formation crops out on the north limb of the Barstow Syncline, is about 300 m thick and overlies and interfingers eastward with the volcaniclastic Pickhandle Formation. The Mud Hills is considered to range in age from about 19.8 - 18.1 Ma, and is interpreted as a sequence of rock avalanche and debris flow deposits that is unconformably overlain by the Barstow Formation on the north limb of the syncline. We note that the  $19.3 \pm 0.02$  Ma Red Tuff found in the lower part of the Barstow Formation on the south limb of the syncline also occurs within the Mud Hills Formation to the north. Figure 8 interprets that the two formations interfinger regionally, especially in that the lower part of the Mud Hills Fm. is considered to have had a southern source; the upper part was derived mainly from the north (Travis and Dokka in Dokka et al., 1991).

The lithostratigraphy, paleomagnetism, biostratigraphy and geochronology of the Barstow Formation in the Mud Hills has been reviewed by MacFadden et al. (1990) and Woodburne et al. (1990), and the following is paraphrased from those sources.

The Barstow Formation is composed of a sequence of fluvial and lacustrine sediments, and water-laid air-fall tuff beds; it is about 1,000 m thick, interfingers with the Pickhandle Formation and is unconformably overlain by Quaternary alluvium in the Mud Hills, and by the Pliocene Black Mountain Basalt in the Gravel Hills (Figure 8). The sediments have been folded into a syncline that trends about east-west and broken by several faults that generally trend northwest-southeast and show right-lateral separation (e.g., Figure 7).



Figure 9 shows the faunal and radioisotopic age relationships of the Barstow Formation in the Mud Hills (Woodburne et al., 1990), with Figure 10 showing its proposed correlation to the Magnetic Polarity Time Scale (after MacFadden et al., 1990).

## CALICO MOUNTAINS

This range is located immediately east and southeast of the Mud Hills (Figure 7). The Calico Mountains contain a thick sequence of eruptive and intrusive volcanic rock of early to medial Miocene age, with minor associated sedimentary deposits. The units, which locally are complexly folded and are cut by northwest-trending faults, unconformably overlie both intrusive rocks of Mesozoic age and Paleozoic carbonate rocks. The Cenozoic units include the Jackhammer Formation, "Formation of Lead Mountain," syntectonic conglomerates and breccias, Pick-handle Formation, "Lane Mountain volcanics," Barstow Formation, and various alluvial units.

The type locality of the Jackhammer Formation is located near Jackhammer Gap in the northwestern Calico Mountains (Figure 7), and has been discussed above (Mud Hills). The unit also crops out in the Lead Mountain

area, about 5 km east of Barstow (Figure 7) where Lambert (1987) shows that it is cut by intrusive dikes dated  $25.6 \pm 0.8$  Ma (Figure 8).

Lambert (1987) also reports that the Jackhammer is unconformably overlain by a unit, indicated here as the "formation of Lead Mountain." This unit is composed of a sequence of tuffs, tuff breccias, lava flows, mudflows, and beds of limestone, sandstone, and conglomerate. The interval is about 2,500 feet (760 m) thick, and composed of a basal unit of rhyodacitic tuff and tuff breccia with individual blocks up to 1 m in diameter; a middle unit of interbedded lapilli ash and tuff, and minor felsite lavas, welded tuff, volcanic mudflows, and tuffaceous sandstones; an upper tuff unit, with interbedded mudflows, basalt, and sandstone. Each of the three units is separated from the others by beds of limestone.

Another unit, here designated as “syntectonic conglomerate and breccia” after Dokka et al. (1988, Figure 9) overlies the other units and apparently is considered to relate to tectonic activities associated with the early Miocene interval of extension in this area. If so, the unit could be significantly younger than the other “Lead Mountain” deposits, as shown on Figure 8.

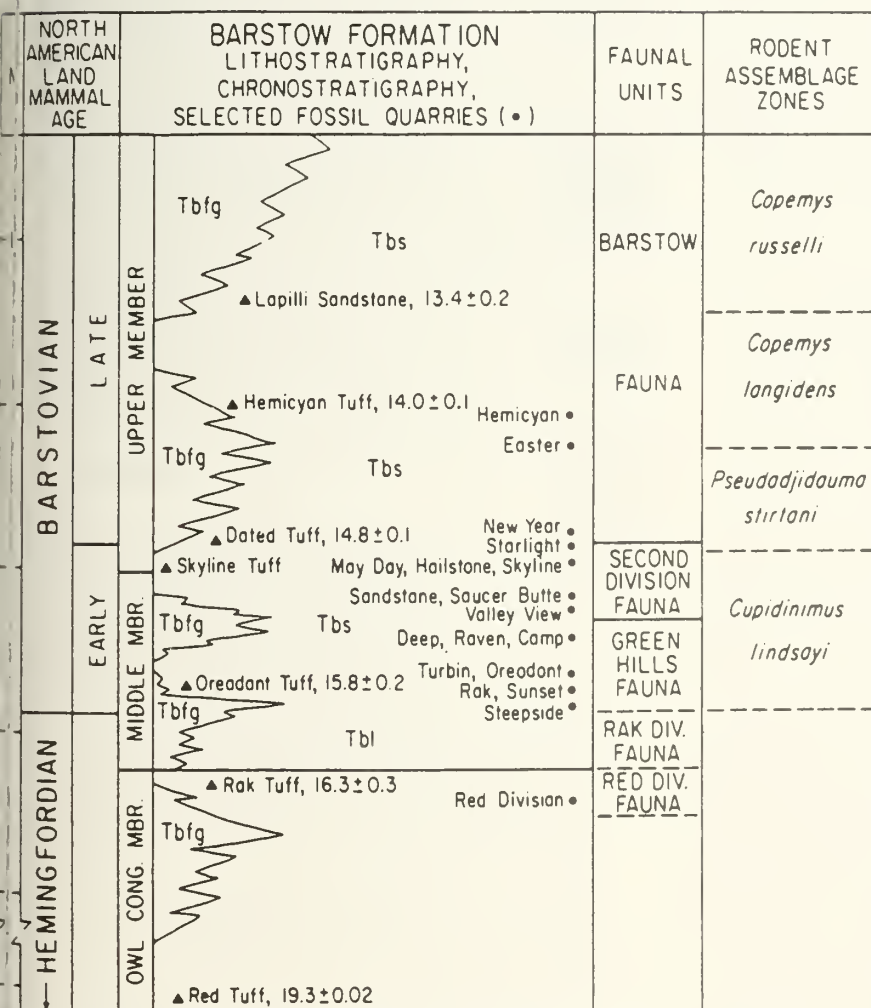


Figure 9. Barstow rock, faunal sequence (after Woodburne et al., 1990)

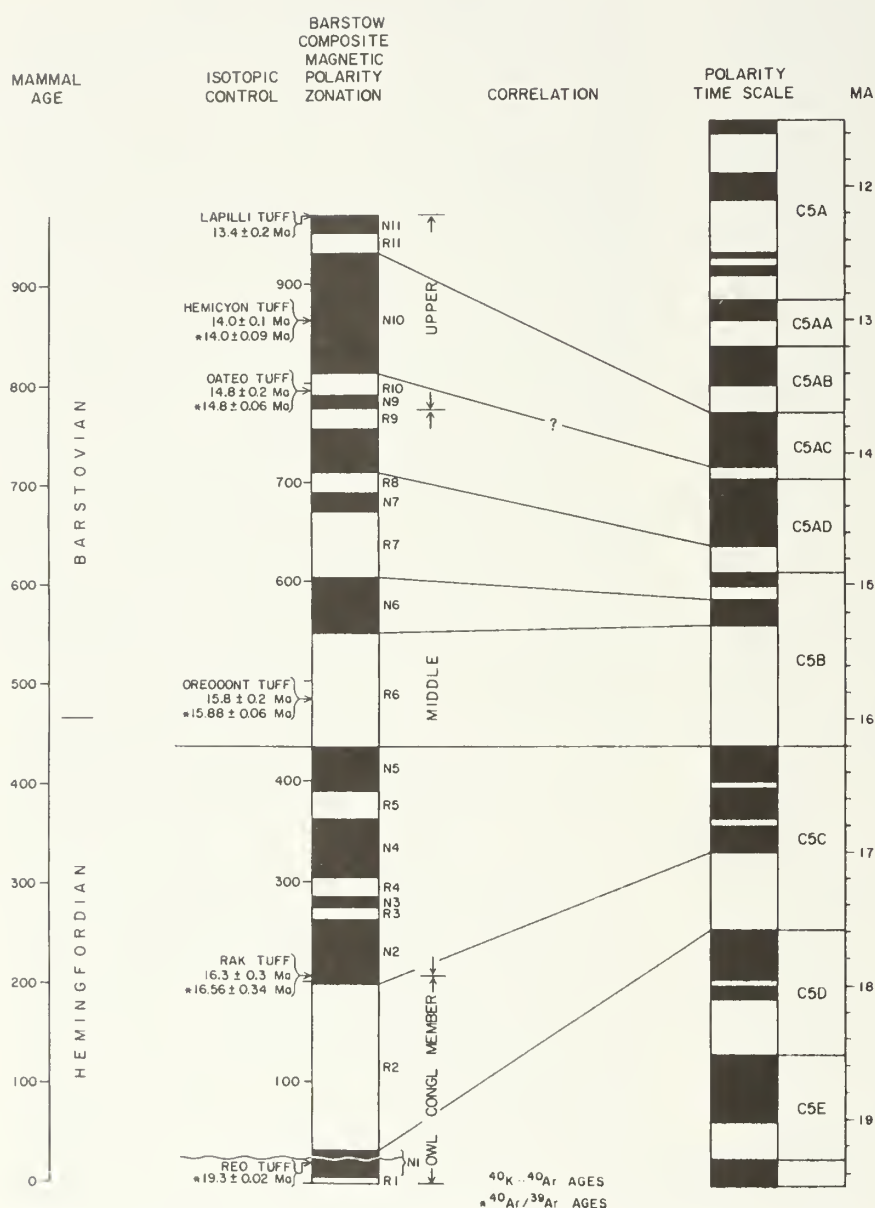


Figure 10. Composite magnetic polarity stratigraphy of the Barstow Formation, Mud Hills, and its correlation to the MPTS (after MacFadden et al., 1990). Date on Valley View Tuff supplied by Carl C. Swisher.

The Pickhandle Formation has been discussed above (Gravel Hills, Mud Hills). In the Calico Mountains the Pickhandle undergoes rapid lateral changes in both lithology and thickness, and becomes more pyroclastic as it is traced from the Mud Hills eastward into its type area, near Pickhandle Pass (Figure 7). Both McCulloh (1954:123) and Dibblee (1968:20, 22) suggest that the Pickhandle reflects a violent interval of volcanic activity and that the "eruptions were separated by intervals of relative quiescence, during which tuffaceous sandstone, conglomerate, and mudflow deposits accumulated" (McCulloh, 1954:123).

Another unit of "Lane Mountain Volcanics," separated from the Lane Mountain Quartz Latite by Burke et al. (1982), is dated at  $18.1 \pm 0.5$  Ma. This age derives from each of the two units, one overlies both the Jackhammer and the Pickhandle formations; the other intrudes the Pickhandle.

The Barstow Formation in the Calico Mountains is exposed in the northwestern, southern, and southeastern parts of the range, and Lambert (1982) maps it in the Lead Mountain area to the south, as well. The unit reaches a thickness of about 1,000 m and consists of a folded sequence of beds in which lacustrine sandstone and shale predominate. Basal beds of limestone are locally present, and intervals of granitic conglomerate occur throughout. Fossil mammals are rare in these deposits, but Dibblee (1970, explanation sheets) notes the local presence of taxa indicating that these rocks have about the same geochronologic span as the fossiliferous part of the unit in the Mud Hills.

The Calico Mountains Barstow Formation appears to represent the lacustrine, basinal, facies of the unit comparable to the conditions inferred for eastern and northern outcrops in the Mud Hills.

### Daggett Ridge

Rocks considered to be part of the extensional, and syntectonic, regime are found in the western Newberry Mountains (Dokka et al., 1988). Unconformably overlying these are fossil-bearing varicolored sandstone, siltstone, and limestone, capped by a freshwater limestone bed of probable Pleistocene age (Reynolds and Lander, 1985). The Daggett Ridge Local Fauna is derived from a lenticular mud-flow breccia with clasts up to 10 cm in diameter. Dokka and Glazner (1982) refer to the strata as Barstow Formation. We note here that these outcrops are physically well removed from the districts that typically contain this formation (see Figures 1 and 3) and hesitate to assign this name to them.

Reynolds and Lander (1985) report the presence of fossil mammals from the Daggett Ridge Local Fauna, suggesting that it is 16 Ma old (Figure 8).



## Yermo Hills

These limited and stratigraphically poorly confined deposits of the Barstow Formation crop out in small hills north of Interstate 15, about 6 km east of the Calico Mountains (Figures 1, 3, and 4). The sequence is about 200 m thick, slightly to strongly tilted toward the north-west, and is overlain by Quaternary alluvium.

The Barstow sediments consist mostly of drab-colored, fine-grained claystone, with minor beds of sandstone, tuff, and limestone. Fossil mammals, the Yermo Local Fauna, are of late Hemingfordian and early Barstovian age, likely about the same as that of the Daggett Ridge Local Fauna.

The fine-grained nature of the clastic units exposed here, coupled with the presence of limestone and water-lain tuff indicate that the Barstow Formation of the Yermo Hills was deposited in a largely lacustrine environment, comparable to the conditions recorded for much of the formation in the Calico Mountains and eastern Mud Hills.

## Alvord Mountain

A relatively complex sequence of deposits of early to medial Miocene age is exposed on the eastern flank of a terrane of Mesozoic plutonic and pre-Cretaceous metamorphic rock in the Alvord Mountain, located about 12 km northeast of the Yermo Hills (Figure 7). The Cenozoic sequence was studied by Byers (1960), who indicates that the late Pleistocene Manix lakebeds also crop out in this district. Major reference to the fossil mammals from the Barstow Formation here is Lewis (1964; 1968a; 1968b). The Miocene rock units are: the Clews Fanglomerate, the Alvord Peak Basalt, the Spanish Canyon Formation, and the Barstow Formation (oldest to youngest).

The base of the Cenozoic sequence is the Clews Fanglomerate, the type locality of which is Clews Ridge (Figure 7). The Clews is about 200 m thick and unconformably overlies plutonic basement rock. The unit was deposited on a former erosional surface with about 300 m of relief, and pinches out westward beneath the Alvord Peak Basalt. This basalt is only of local occurrence and pinches out to the east, where the Clews Fanglomerate is overlain with possible unconformity by the Spanish Canyon Formation (Figure 8).

The Clews is mostly composed of red-brown conglomerate with blocks of mafic plutonic rock up to 3 m in diameter. Most of the unit appears to have been derived locally from the near-by range and to reflect tectonic events in the immediate area.

The age of the Clews is unknown. That shown on Figure 8 is based on general stratigraphic relationships and the suggestion that the pyroclastic materials of the

Spanish Canyon Formation are correlative with those of the Pickhandle Formation to the west.

The Alvord Peak Basalt, about 100-125 m thick, is located mainly west of Spanish Canyon (Figure 7), and thins eastward. The Alvord Peak Basalt conformably overlies the Clews Fanglomerate, and dikes and pipes of basaltic rock locally cut the Clews. The Alvord Peak Basalt is composed of multiple flows, and is usually overlain by the Spanish Canyon Formation but, locally, by the Barstow Formation.

The age of the Alvord Peak Basalt is unknown.

The Spanish Canyon Formation is about 100 m thick. It conformably overlies the Alvord Peak Basalt and the Clews Fanglomerate; it is locally conformably overlain by the Barstow Formation, unconformities found in other places (Byers, 1960:22) indicate that there is a hiatus between the two units. The Spanish Canyon Formation is of limited areal extent and pinches out to the west.

In addition to locally-derived detritus, such as granitic and mafic boulder conglomerate, the Spanish Canyon Formation contains upper flows of olivine basalt, and tuff beds. Byers (1960) interpreted the tuffs to record a major explosive volcanic event or events in the central Mojave Desert, and suggested on the basis of microscopic analysis that they correlate with the Pickhandle Formation to the west.

The Barstow Formation crops out in the eastern part of the Alvord Mountain and consists of "clastic and tuffaceous beds that are characterized by lithology and vertebrate fossils similar to or identical with those found in the Barstow Formation at the type locality [and] are assigned to [that formation]..." (Byers, 1960:26). The lithic features characteristic of the Barstow Formation in more western districts do, however, differ in many ways from the rocks correlated with the Barstow Formation in Alvord Mountain, and the differences are especially striking when these deposits are compared to the primarily lacustrine sediments in the Yermo Hills, the geographically closest sequence. While not wishing to belabor this point here, we emphasize the probably more marginal setting of the Barstow Formation in Alvord Mountain relative to the depositional setting found in sites to the west. In fact, the Barstow becomes coarser-grained to the northeast (MOW, pers. observation).

The Barstow Formation in the Alvord Mountain is about 400 m thick, and is divided into three members. The formation overlaps the Alvord Peak Basalt, is basically unconformable on the Spanish Canyon Formation as well as on older units; the upper contact is locally gradational and conformable with overlying granitic fanglomerate (Byers, 1960:27), but in places there is a slight angular unconformity, and local channels also are present.



The lower member of the formation consists of about 175-200 m of interbedded sandstone and pebble conglomerate, overlain by 50-175 m of tuff, tuffaceous sandstone, siltstone, and volcanic pebble conglomerate. Three flows of olivine basalt occur in the lower 60 - 100 m of the unit, adjacent to Clews Ridge. C.C. Swisher (personal commun., 1991) has obtained  $^{40}\text{Ar}/^{39}\text{Ar}$  ages of  $16.47 \pm 0.5$  Ma on the lower of these basalts near Clews Ridge and  $16.6 \pm 0.2$  Ma on the correlative unit in Spanish Canyon. R.E. Reynolds reports the presence late Hemingfordian mammals a few meters below the lowest basalt in Clews Ridge. Fossil mammals found in stratigraphically higher parts of the Barstow Formation here support the correlation shown in Figure 8. C.C. Swisher (personal commun., 1991) reports a mean age of  $14.4 \pm 0.03$  Ma on plagioclase and biotite from the upper middle member tuff consistent with these correlations.

## Cady Mountains

Dibblee and Bassett (1966a, b) mapped the regional geology of the area, and indicate that the Tertiary succession here (Figure 7) is arranged largely peripheral to a central core of pre-Tertiary plutonic rock and metamorphic rock of limited areal extent. Major outcrops of Miocene sedimentary rock occur on the northern and western flanks of the range but, toward the center, extensive units of volcanic rock are shown. As discussed below, these rocks are likely mostly older than the main sedimentary succession, and pertain to a volcanic center that was active as early as 23-24 m.y. ago. Nonmarine fluviatile, volcanoclastic, and pyroclastic deposition (Hector Formation) began locally by about 23 Ma, and persisted until at least 16 Ma, prior to the development of a major hiatus. The Peach Springs Tuff, a regional marker unit dated at about 18.5 Ma (Nielsen et al., 1990) likely was present in this sequence as well.

Subsequent to Hector Formation deposition, the region underwent at least  $26^\circ$  of clockwise rotation (MacFadden et al., 1990), but geological evidence younger than the Hector deposits is sparse or, if present, poorly dated. The Manix Formation (Jefferson, 1985) and precursors show that the Central Mojave Desert was occupied by one or more regional lakes from 2 Ma to about 19,000 years. Dokka and Travis (1990a, b) point to the recency of geologic events in this area. The Manix fault, one of a family of west-trending faults with left-lateral separation, experienced a major (ca 6.2) earthquake in 1947 (Richter, 1947; Real et al., 1987).

The following discussion begins with the Tertiary succession of the southwestern Cady Mountains, which contains the geologically oldest biochronological data, and is followed by comments on successions exposed on the northern and eastern flanks of the range.

Southwestern Cady Mountains.—Woodburne et al. (1974) indicate that the base of the Tertiary succession in the southwestern Cady Mountains begins with andesitic lahar and agglomerate and interbedded tuffaceous sediments that rest unconformably on pre-Tertiary basement rock. As mapped, this succession is not named, but seems comparable to pre-Hector units mapped in the northeastern Cady Mountains (Williamson, 1980).

The Miocene strata of the Hector Formation are about 500 m thick; they unconformably overlie the agglomerate units and are unconformably overlain by Quaternary alluvium. The Hector sediments (Woodburne et al., 1974) are divided into a largely tuffaceous and volcanoclastic lower sequence (below the marker tuff bed on Figure 7) and an upper succession that, although of tuffaceous matrix, included many fewer beds of tuff. The Peach Springs Tuff may be present in this section, however (Woodburne and T. Ross, pers. observation, 1991; see also Woodburne et al., 1974, Figure 3, unit Tho). A tuff near the top of the lower sequence has been dated (revised [Dalrymple, 1979] from Evernden et al., 1966) at about 21.6 Ma. If the Peach Springs Tuff is present in the upper sequence, that would indicate an age of about 18.5 Ma for part of it.

Fossil mammals from the Black Butte Mine Local Fauna occur in the lower part of the succession, below the marker tuff (Figure 8) and appear to be of late Arikarean age (Wood et al., 1941: for all mammal ages used here, but see also Woodburne, 1987). The Logan Mine Local Fauna occurs in beds that stratigraphically overlie those of Black Butte Mine, and includes fossils that Woodburne and Whistler (1973) and Woodburne et al. (1974) originally considered to be of early Hemingfordian age. Revisions in the stratigraphy of the pertinent beds and faunas in Nebraska (Hunt, 1978; 1981) indicate that some of the Hector Formation local faunas are of late Arikarean age (Tedford et al., 1987).

Regionally, faunas of late Arikarean age are calibrated as ranging from 23 - 20 m.y. (Tedford et al., 1987), but the Black Butte Mine Local Fauna is plausibly no older than about 22 Ma. The Logan Mine Local Fauna may in part be younger than 18.5 Ma if the possible presence of the Peach Springs Tuff in beds near the middle of the section is borne out.

Northern and eastern Cady Mountains.—The geology, paleontology, and isotopic age of the Hector Formation in the northern Cady Mountains have been described by Miller (1980), Moseley (1978), and Williamson (1980; see Figure 7 for locations). Williamson (1980) studied the dominantly extrusive volcanic succession north of the Cady fault in the eastern part of the range. A major unconformity apparently separates this volcanic succession from the upper part of the Hector Formation, as mapped by Williamson (1980).

Miller (1980) indicates that the Hector Formation as exposed on the northern flank of the range contains a succession of tuffaceous and volcanoclastic sedimentary rock, interbedded with a flow of olivine basalt and a distinctive ignimbrite unit. The deposits have been gently deformed into a shallow syncline that trends east-west and plunges shallowly to the east. The beds have been cut by a number of faults that trend generally northward and have a dip-slip throw of about 100 m at most.

The two volcanic units are used to divide the sequence into three intervals. The lowest begins with a succession of tuffaceous sediment, tuff, and derivative ignimbritic rock that is about 100 m thick. Tuffs near the local top of this sequence have been dated at  $22.9 \pm 0.4$  Ma (Miller, 1980), and a basalt that overlies this interval has been dated at 18.6 Ma.

The middle part of the Hector Formation in this area continues upward from the just-mentioned basalt for about 85 m, where it is capped by a distinctive ignimbrite dated at  $17.9 \pm 0.3$  Ma (Miller, 1980). The rocks of this interval are generally similar to those of the lower part, and are mostly thin-bedded intervals of plausibly lacustrine accumulation. To the southwest, however, coarser-grained, more marginal facies, prevail.

The Lower Cady Mountains Local Fauna, of approximately late Arikarean to early Hemingfordian age is represented by sparse but significant fossil mammals that occur in this part of the section from about 30 m below the basalt to about 30 m above it. Taxa in the lower interval (30 m below the basalt) are compatible with a late Arikarean age.

Sparse fossil mammals occur in the beds that lie 16–30 m above the basalt, and are also attributed to the Lower Cady Mountains Local Fauna. These taxa are similar to those found in the early Hemingfordian Boron Local Fauna to the west (Whistler, 1984).

The upper part of the Hector Formation begins with a brown to brownish gray to orange-brown and locally reddish-gray ignimbrite about 17 m thick. The upper unit rests conformably on the unit is about 130 m thick, and consists of tan to greenish gray and tan tuffaceous sandstone, mudstone, tuff, and local lenses of conglomerate. A thick unit of nonmarine limestone occurs near the top of the sequence.

The Upper Cady Mountains Local Fauna occurs just above the massive limestone interval, about 65 m stratigraphically above the ignimbrite. The faunal elements, which occur within a range of a few tens of meters, include taxa assigned a late Hemingfordian age, or about 16 Ma.

The Afton Canyon district, mapped by Moseley (1978) comprises a 570 m thick sequence that correlates best with the lower and middle parts of the Hector Formation of Miller (1980). The rocks form a sequence of alluvial and lacustrine strata, interbedded with lahatic breccia, and a sequence of volcanic rocks, air-fall tuff, a major ignimbrite, and flows of basaltic to andesitic lava. No fossils have been reported, but coarser-grained facies suggest that the local basin margin was not far away to the east.

## Avawatz Mountain

Avawatz Mountain (Figure 2) is exposed at the junction of the Garlock fault and the Death Valley fault zone (Figures 1 and 2). The range contains a variety of Precambrian metasedimentary, Paleozoic clastic and carbonate units, Mesozoic granitic rock, and Tertiary sediments (e.g., Spencer, 1990a). Along the southern and western flank, the Avawatz Formation crops out and locally contains terrestrial mammal fossils.

The Avawatz Formation is several thousand feet thick. Spencer (1990b) divides the unit into an upper and lower sandstone and siltstone facies and a middle facies of conglomerate. The lower part of the formation, at least 1,000 m thick, contains a tuff near its base that has been dated at  $20.9 \pm 0.2$  Ma (Figure 8), and accumulated mostly west of the Arrastre Spring fault. This fault now bounds the western part of the range, and apparently was active during the deposition of the lower Avawatz Formation. Those beds include clasts not derivable from the present range, but must have come from sources to the east, now buried or displaced. The Avawatz thus records events both on and adjacent to the present boundary of the Mojave Desert Province.

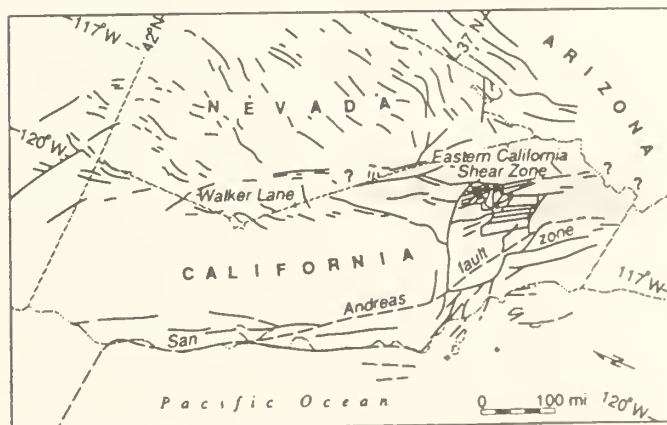


Figure 11. Eastern California Shear Zone. From Dokka et al., 1991.

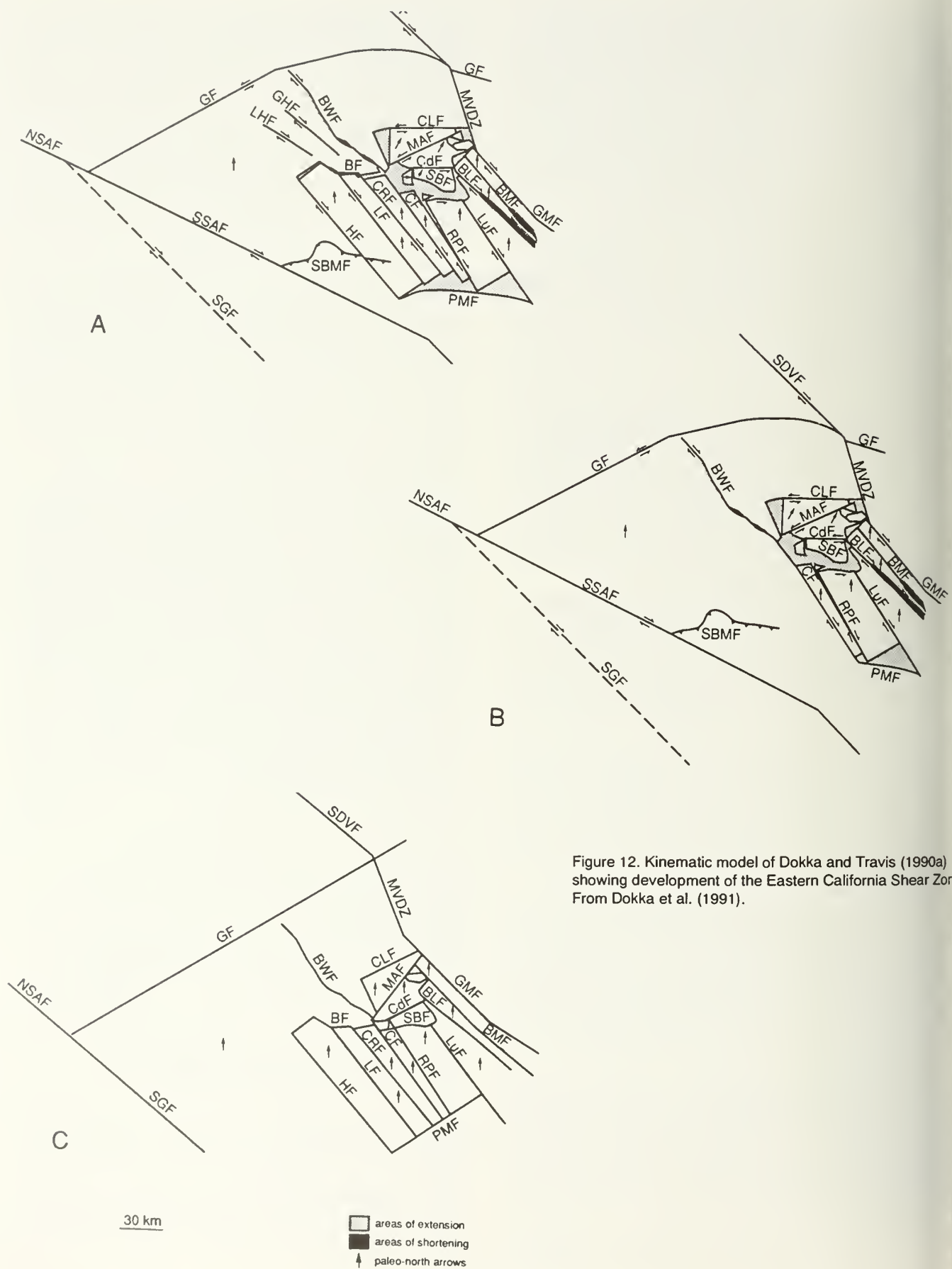


Figure 12. Kinematic model of Dokka and Travis (1990a) showing development of the Eastern California Shear Zone. From Dokka et al. (1991).



The upper part of the Avawatz Formation contains sandstone, locally gypsiferous siltstone, and beds of thin, welded tuff. Spectacular areally extensive sheets of breccia also interbedded in the section and can form convenient lithic as well as temporal markers.

The Avawatz Local Fauna of Clarendonian age has been known since about 1937 (Henshaw, 1939). Evensen et al (1964) recorded a K-Ar date of about 11.0 Ma from a tuff that apparently is stratigraphically about 30 m above C.I.T. 267, the main fossil-producing locality in the upper part of the formation (Figure 8).

## Tectonics of the past 10 Ma

This effectively follows Dokka and Travis (1990a, b), and Dokka et al. (1991). Examples given above suggest that various sequences of effectively Miocene age have been rotated and disrupted subsequently. Exactly when these post-Miocene events transpired is difficult to determine due in part to the missing "5 million year gap" alluded to above. Certainly many northwest and east-west trending faults are still active today (see above), suggesting that the accompanying predicted senses of deformation and rotation still are effective. The 1992 Landers earthquake (see references above) show that the Eastern California Shear Zone (Dokka and Travis, 1990a, b) still is active, although Sieh et al. (1993) suggest that recurrence on at least the Landers segment of this zone is

on the order of millenia rather than centuries (in contrast to the San Andreas fault zone). Atwater (1970) proposed that strain across the Pacific-American plate boundary would be accommodated via a wide span of deformation that extended well eastward of the San Andreas fault. Dokka and Travis (1990a, b) propose that the Mojave Desert Province can be characterized as being comprised of six domains, some of which show significant dislocation and rotation during the past 10 (~ 6) Ma, with the eastern boundary of the shear zone (Figures 11 and 12) being defined by the southern Death Valley fault, the Mesquite Valley Disturbed Zone and the Granite Mountains fault (an extension of which would reach the Pinto Mountain fault). The model suggests that shear is not uniformly distributed across the Mojave Desert Province during this time and that, in fact, the Antelope Valley was virtually unaffected. Nevertheless, approximately 65 km of regionally cumulative right shear was accommodated across this zone. Approximately peripheral to the present Cady Mountains, however, adjustments between displaced and rotated blocks produced gaps in the crust that now correspond to relatively recent features, such as Troy, Broadwell, and Soda lakes, Pisgah Crater, etc. Apparently many of the relatively young geological features we see on the Mojave Desert Province attest to the recent, and likely continuing, displacement of parts of it.

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# Brine Mineral Occurrence in the Diablo Mountain Study Area, Oregon, and its Possible Significance to Pacific Rim Trade

by

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## ABSTRACT

At the request of the U.S. Bureau of Land Management, the U.S. Bureau of Mines and U.S. Geological Survey conducted a mineral investigation of about 85,470 acres of the Diablo Mountain Wilderness Study Area, to determine mineral resources and mineral resource potential. The study area is in Lake County Oregon, about 45 miles northwest of Lakeview. Fieldwork was conducted in 1986, 1988, and 1989.

Geologically, the study area lies on the northwest edge of the Basin and Range physiographic province, a region of fault block-formed mountains and basins characterized by interior drainage. Consolidated rocks are mostly Tertiary basalt and tuffaceous sedimentary rocks. Low-lying areas are covered by Quaternary alluvial-fan, sand-dune, playa, lacustrine, and landslide deposits. The principal structural features are normal faults that have large vertical offsets; these faults are typically concentrated at the margins of large horst and graben.

The 34,310-acre "additional," or western part of the area was mainly studied in 1988 and borders the east shore of saline Summer Lake. In this portion of the study area there is potential for undiscovered resources of soda ash, boron compounds, and sodium sulfate as well as by-products, which include magnesium compounds, salts, potash, bromine, lithium, and tungsten associated with brines.

No energy or mineral resources were identified in the study area, but brines within lake and playa sediments contain concentrations of chemical components suitable for the production of soda ash, boron compounds, and sodium sulfate. Possible by-products include potash, salts, bromine, lithium, magnesium compounds, and tungsten. Limestone from the study area could be used in the recovery process of brine components or agricultural uses. The study area includes thermal springs and lies within 2 miles of the Summer Lake Known Geothermal Resource Area. Local production of geothermal power by the binary process may be economically feasible.

Soda ash, soda ash products, and boric acid are widely used in fluxing metals, and have important applications and markets in the aluminum industry in the northwest and the developing Chinese counterpart. Evaporite commodities are essential to many "backbone" industries, and to many new applications and advanced materials. Markets for brine mineral products appear to be undergoing steady and strong growth, especially in the Pacific Northwest and in Pacific Rim countries. Soda ash produced near the study area would be 55 percent closer by rail to marine export at Portland, Oregon, than trona deposits of the Green River District (Wyoming).

Soda ash and a daughter product, caustic soda, and sodium borohydride will receive increased application in the bleaching of paper pulp for environmental reasons. Caustic soda, used in many industrial processes, is more environmentally friendly when derived from soda ash than when produced from sodium chloride salt, because of the absence of a chlorine by-product. Producing soda ash from brines, a type of "in situ" mining, can be done with minimal environmental degradation, and mining natural soda ash is environmentally as well as economically preferable to synthetic soda ash production.

## INTRODUCTION

A brine mineral occurrence of possible economic significance was documented along the east shore of Summer Lake, Lake County, Oregon, in the western or "additional" portion of the Diablo Mountain Wilderness Study Area. This finding is the result of a mineral survey requested by the U.S. Bureau of Land Management (Figure 1). The various phases and conclusions of the study, reported by Diggles and others (1990 b), result from a cooperative effort by the U.S. Bureau of Mines and the U.S. Geological Survey. The U.S. Bureau of Mines evaluates identified resources at individual mines and known mineralized areas by collecting data on current and past mining activities and through field examination of mines, prospects, claims, and mineralized areas. Resources are classified according to a system that is a modification of that described by McKelvey (1972), and the U.S. Bureau of Mines and U.S. Geological Survey (1980).

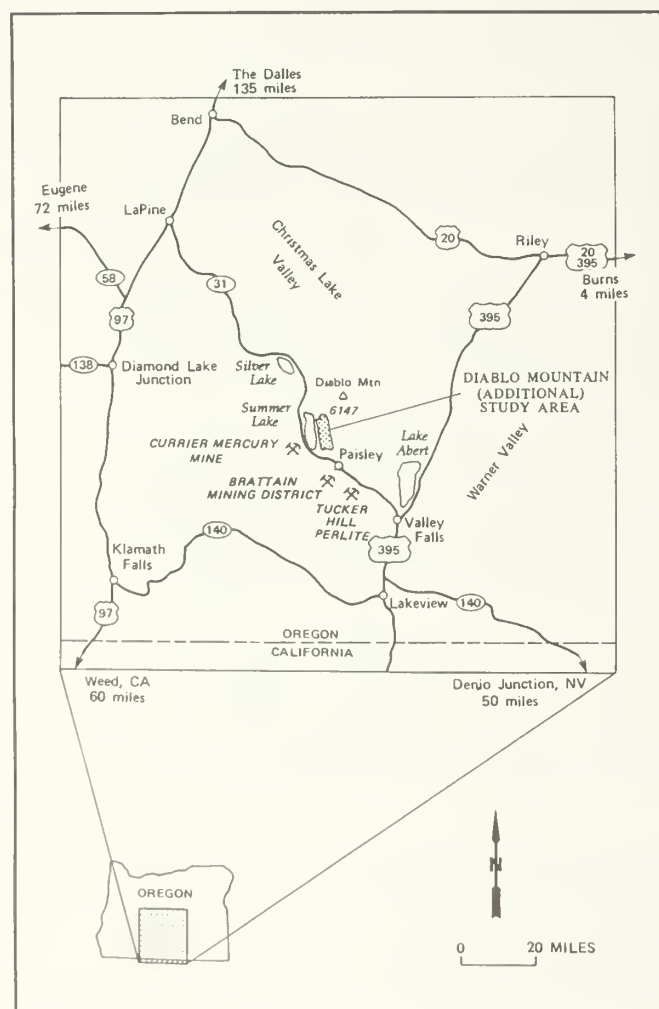


Figure 1. Location of the Diablo Mountain (Additional) study area, Lake County, Oregon (from Peters and Willett, 1989).

U.S. Geological Survey studies are designed to provide a scientific basis for assessing the potential for undiscovered mineral resources by determining geological units and structures, possible environments of mineral deposition, presence of geochemical and geophysical anomalies, and applicable ore-deposit models. An introduction to the wilderness review process, mineral survey methods, and agency responsibilities were provided by Beikman and others (1983). Goudarzi (1984) discusses mineral assessment methodology and terminology applicable to these surveys.

## LOCATION AND PHYSIOGRAPHY

The Diablo Mountain Wilderness Study Area includes approximately 85,470 acres and is situated 45 miles north of Lakeview and 5 miles north of Paisley, Oregon (Figure 1). Elevations in the area range from 4,300 feet near the shore of Summer Lake to 6,147 feet at the summit of Diablo Mountain. Access to the region is via Oregon State Route 31 connecting U.S. Highways 395 north of Lakeview and 97 south of Bend. Access to the area is provided by two-wheel-drive dirt roads leading off State Highway 31.

Access within the study area is by four-wheel-drive vehicle on jeep trails and by mountain bicycle and by foot. The climate is semiarid, and the average annual precipitation is about 12 inches; the sparse rainfall in the area results in only intermittent stream flow. The region contains several lakes, of which Summer Lake is one, that occupy closed basins. Vegetation consists of low-growing desert shrubs, mostly sagebrush, greasewood, creosote bush, burroweed, and boxthorn.

## SETTING

The Diablo Mountain Wilderness Study Area is just east of Summer Lake (Figure 1) and lies on the northwest edge of the Basin and Range physiographic province, in the volcanic plateau region lying south of the Blue Mountains and east of the Cascade Range. The region west of Summer Lake and continuing south of the study area is part of the poorly defined Modoc Plateau physiographic province that separates the Basin and Range and the Cascade Range physiographic provinces.

Consolidated rocks within the study area consist mostly of Tertiary basalt and tuffaceous sedimentary rocks. The low-lying areas are covered by Quaternary alluvial-fan, sand-dune, playa, lacustrine, fluvial, and landslide deposits. The principal structural features of the area are normal faults that have large vertical offsets. These faults are concentrated at the margins of large horsts and grabens and are typical of the Basin and Range Province.

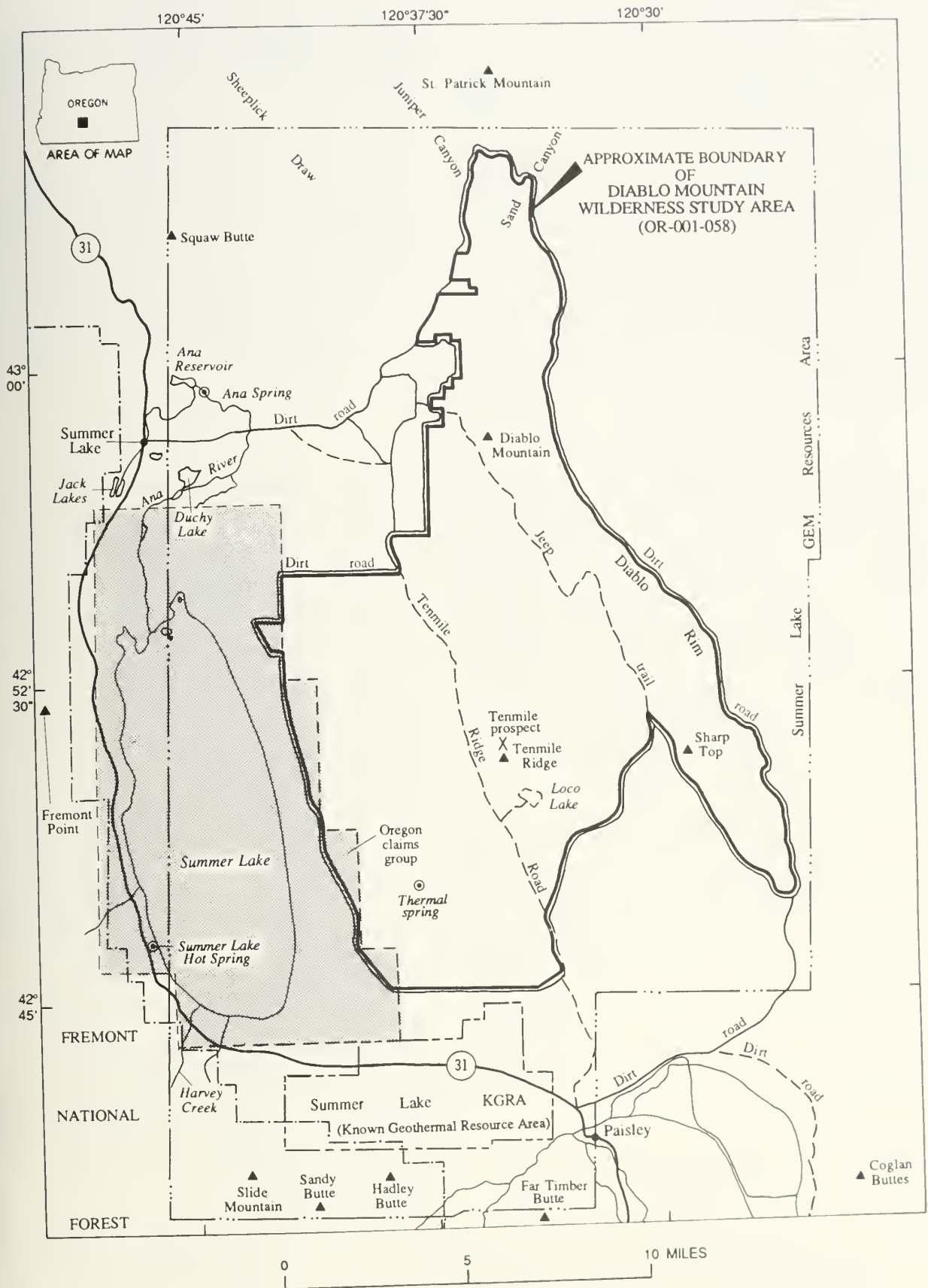


Figure 2. Diablo Mountain Wilderness Study Area and adjacent Oregon (prospect) claims group, Lake County, Oregon (from Diggles and others, 1990b).



## Previous Studies

Waring (1908) discussed the geology and water resources of south-central Oregon. The eastern halves of the Klamath Falls and Crescent 1° by 2° quadrangles were mapped by Walker (1963) and Walker and others (1967), respectively. Peterson and McIntyre (1970) presented the geology and mineral resources of part of Lake County. An assessment of geology, energy, and minerals in the Summer Lake GEM Resources Area (Figure 2), is presented in Mathews and others (1983). Geology of the Summer Lake area is discussed more extensively in Conrad (1953) and Travis (1977). Mineralized waters at Summer Lake were discussed by Van Denburgh (1975). Structural geology of the Summer Lake area is emphasized in Fuller and Waters (1929), Donath (1962), Donath and Kuo (1962), and Lawrence (1976).

## Procedures

The U.S. Bureau of Mines work on the Diablo Mountain Wilderness Study Area was done in two phases. The central and eastern parts of the area were examined by Willett (1987), and the western part of the area was studied by Peters and Willett (1989). These studies included library search of pertinent geological and mining literature. U.S. Bureau of Land Management master title plats and current mining claim recordation data, as well as Lake County mining claim records were examined. Information was also obtained from the U.S. Bureau of Land Management Lakeview District Office, the Oregon Department of Geology and Mineral Industries, Portland, and the U.S. Bureau of Mines Mineral Industries Location System and other files and records.

U.S. Bureau of Mines field work was done during spring 1986 and June 1988. A search was conducted for all mines, prospects, and mineralized areas in and within 1 mile of the study area. Samples include: 45 sediment, 2 brine, 26 water (predominantly from auger holes), 21 alkali crust (from surfaces of alkali flats adjacent to auger holes), 34 rock (randomly chipped from homogeneous outcrops), and 4 sand samples; 1 auger-hole sediment sample was collected for mineral identification by x-ray diffraction (halite). Mineralized sites were examined and sampled. Results of analyses of these samples are on file at the U.S. Bureau of Mines, Western Field Operations Center, E. 360 Third Ave., Spokane, WA 99202.

The U.S. Geological Survey conducted detailed field investigations of the Diablo Mountain Wilderness Study Area in the summers of 1986, 1988, and 1989. This work included making a detailed geologic map (Diggles and others, 1990a), collecting geochemical, petrologic, and geochronologic samples, and examining outcrops for evidence of mineralization. The geological studies are

reviewed below; for information on geochemical and geophysical investigations the reader is referred to Diggles and others (1990b) and U.S. Geological Survey (1972).

## GEOLOGY

### Stratigraphy

The Diablo Mountain Wilderness Study Area is underlain by sedimentary and volcanic rocks of Tertiary and Quaternary age (Figure 3). They are generally flat lying but are broken by normal faults. Tertiary rocks in the study area consist of tuffaceous sedimentary rocks, basaltic flows, basaltic pyroclastic rocks, tuffaceous sedimentary rocks, rhyolitic tuff, and dolomitic limestone.

#### Description of map units

Qal	Alluvium (Quaternary)—Alluvial fan deposits and stream deposits of gravel, sand, and silt
Qsd	Sand dunes (Quaternary)—Large areas of wind-blown sand composed of ash, pumice, and rock-fragments and mineral grains, mostly alkali feldspar and quartz
Qpl	Playa deposits (Quaternary)—Clay, silt, sand, and some evaporite deposits. Contains tephra at depth
Qlf	Lacustrine and fluvial deposits (Quaternary)—Unconsolidated clay, silt, and gravel
Qls	Landslide deposits (Quaternary)—Unstratified mixtures of basaltic and tuffaceous sedimentary rocks. Includes faulted blocks, rubble, and talus
Qcl	Claystone (Quaternary)—Mostly montmorillonite; locally includes marl, micrite, caliche, and caliche-bearing travertine
Tbc	Basaltic cinders (Tertiary)—Red and reddish-brown cinders and near-vent flows; scoriaceous rock and altered basalt
Tb	Basalt (Tertiary)—Gray to dark-gray plagioclase-phyric olivine basalt flows having subophitic to diktytaxitic texture. Includes minor basaltic breccia. Crystals of labradorite are partly to completely enveloped in clinopyroxene. Pyroxene also forms interstitial grains. Locally interbedded with dolomitic limestone of Pliocene(?) age in vicinity of Tenmile Ridge (see fig. 1)
Tts	Tuffaceous sedimentary rocks (Tertiary)—Semi-consolidated interbedded white, light-yellow and cream-colored lacustrine and fluvial sedimentary rocks that consist mostly of tuffaceous sandstone and siltstone and locally contain arkosic sandstone and pebble conglomerate. Contains alkali feldspar, clay minerals, zeolites, and secondary silica minerals. Age and correlation uncertain but presumably mostly of middle and late Miocene age (Walker, 1977)

—— Contact

----- Fault—Dashed where approximately located, cted where concealed

X Tenmile prospect



Figure 3. Generalized geology and mineral potential of the Diablo Mountain Wilderness Study Area, Lake County, Oregon (from Diggles and others, 1990b).



Tuffaceous sedimentary rocks underlie much of the study area. They are semiconsolidated, interbedded white, light-yellow, and cream-colored lacustrine and fluvial sedimentary rocks that consist mostly of tuffaceous sandstone and siltstone and locally contain arkosic sandstone and pebble conglomerate. They contain alkali feldspar, minor amounts of clay minerals, zeolites in amygdules, and secondary silica minerals. Their age and correlation are uncertain, but they are presumably mostly of middle and late Miocene age (Walker, 1977).

Basalt flows underlie most of the high country in the study area. The basalt is medium-gray to dark-gray, contains plagioclase phenocrysts and olivine, and has subophitic to diktytaxitic texture. Crystals of labradorite are partly to completely enveloped in clinopyroxene. Pyroxene also forms interstitial grains. The basalt is olivine-normative tholeiite (Irvine and Barager, 1971) rich in aluminum, magnesium, and calcium oxides ( $\text{Al}_2\text{O}_3$ ,  $\text{MgO}$ ,  $\text{CaO}$ ) and depleted in titanium, sodium, and potassium oxides ( $\text{TiO}_2$ ,  $\text{Na}_2\text{O}$ , and  $\text{K}_2\text{O}$ ). A potassium-argon age determination on a basalt sample from the Diablo Rim shows an age of  $6.3 \pm 0.4$  million years (Ma), or latest Miocene (Diggles and others, 1990b). The underlying tuffaceous sedimentary rocks erode readily and cause landslides of the basalt.

A dolomitic limestone of Pliocene(?) age north and east of Tenmile Ridge is locally interbedded with the basalt flows. It is present on the flanks of the ridge and crops out discontinuously among the dunes to the northwest.

Red and reddish-black basaltic cinders and near-vent flows crop out in one area on Tenmile Ridge. These are unconsolidated, fine to coarse scoriaceous oxidized rocks. Luedke and Smith (1982) report this volcanic center as a basaltic (46-54 percent silica) cinder cone with an age of less than 5 Ma. A recently determined potassium-argon age of the cinders, however, is  $6.6 \pm 0.3$  Ma (Diggles and others, 1990b). The cinders are quartz-normative alkali-olivine basalt (Irvine and Barager, 1971) rich in titanium, sodium, and potassium oxides ( $\text{TiO}_2$ ,  $\text{Na}_2\text{O}$ , and  $\text{K}_2\text{O}$ ) and depleted in magnesium and calcium oxides ( $\text{MgO}$  and  $\text{CaO}$ ). Locally, zones of altered basalt flows are cut by veinlets and dikelets of opal-bearing travertine. Locally vesicular basalt flows are altered and amygdaloidal; minor amounts of zeolite fill some amygdules. There is also minor basalt-flow breccia in the study area.

Quaternary deposits consist of alluvium, dune, playa, lacustrine, fluvial, landslide, and claystone deposits. The alluvium consists of unconsolidated deposits of sand, gravel, ash, and pumice that formed in flood plains and fill the stream channels.

The dune sand is composed of ash, pumice, and mineral grains, mostly alkali feldspar and quartz. Playa deposits are made up of clay, silt, sand, and some evaporites, and contain tephra at depth (Simpson, 1989). Lacustrine and fluvial deposits consist of unconsolidated clay, silt, and gravel. They are commonly covered by meadow or marsh vegetation. Landslide deposits, present mostly on the east flank of Diablo Rim, are unstratified mixtures of basalt and tuffaceous sedimentary rock. Here, as elsewhere, they commonly develop where a basalt rim overlies tuffaceous sedimentary rocks. The claystone consists mostly of montmorillonite produced by decomposition of volcanic ash and locally includes deposits of marl, micrite, caliche, and opal-bearing travertine.

The Summer Lake Basin was occupied by pluvial Lake Chewaucan. Sediments in the basin include tephra from several large volcanic eruptions. Landslides from Winter Rim, west of Summer Lake, between 19 and 12 thousand years ago locally compressed and deformed the sediments (Simpson, 1989).

## Structure

The study area lies on the northwest edge of the Basin and Range physiographic province. Summer Lake occupies a closed basin bounded by ridges that have fault-scarp fronts (Phillips and Van Denburgh, 1971). The structural geology of the study area is dominated by high-angle north-northwest-trending normal faults that have cut the range into blocks. J.J. Rytuba (oral communication, 1989) suggested that the Summer Lake area, including the area to the east, now covered with dunes, may be a late caldera and may have associated gold resource potential. G.W. Walker (oral communication, 1987), however, noted that no known ash-flow tuff sheet is correlated with the basin. The concurrence of regional north-northwest-trending fault zones with older caldera structures and silicic intrusions is emerging as one of the most viable means of locating gold deposits in this part of the Basin and Range (Rytuba, 1989).

The Diablo Rim is the most extensive scarp resulting from this faulting (Figure 3). The study area is bounded on the northeast by the north-northwest-trending Brothers Fault Zone that has been interpreted as a transcurrent structure that bounds the northwest edge of the Basin and Range physiographic province (Lawrence, 1976). The area on the west side of Summer Lake and south of the study area is part of the poorly defined Modoc Plateau physiographic province that separates the Basin and Range and the Cascade Range physiographic provinces (Macdonald, 1966). Vertical offset in the study area is apparent at the margins of large fault-bounded horsts and grabens typical of the Basin and Range.



Linear features of every orientation are well expressed on the surface in southeastern Oregon, except in the volcanic terrane. Local lineaments are related to significant faults or to rock joint systems. No linear features in the study area were discovered by remote sensing except along the faults already discussed. The region surrounding the study area have two prominent structural trends. The dominant trend of N. 20° W. is concentrated northwest of the study area. The second trend, of 20° E., consists of three aligned linear features as long as 6 miles that lie northeast of the study area.

The presence of a felsic intrusive body in the area has been inferred from the aeromagnetic and gravity-anomaly data (Diggles and others, 1990b). The Summer Lake caldera may be a caldera-formed feature (J.J. Rytuba, oral communication, 1987). The regional north-northwest trending fault zones cutting caldera structures and silicic volcanic centers are emerging as an indicator of gold-silver mineral deposits in the northern Basin and Range (Rytuba, 1988; 1989).

### Mineral Resource Potential

The mineral resource potential of the Diablo Mountain Wilderness Study Area is moderate for commodities associated with brines in the western (Additional) part of the study area (Diggles and others, 1990b). Commodities that may be present beyond known occurrences are soda ash, boron compounds, and sodium sulfate; possible by-products include magnesium compounds, salts, potassium, bromine, lithium, and tungsten.

The Summer Lake Known Geothermal Resource Area (KGRA) is 2 miles south of the study area. There are thermal springs (66° C) at Ana Springs north of the study area (Waring, 1908; Brown, 1957) and a thermal spring at Summer Lake Hot Spring south of the study area. A thermal spring and thermal water at a sample-collection site are present within the study area, indicating the area has moderate geothermal energy resource potential for low-temperature geothermal energy.

The mineral resource potential is low in the area of Tenmile Ridge for low-grade, high-tonnage epithermal hot-spring gold-silver deposits of the type defined by Singer (1985; 1986), Berger and Silberman (1985), and Singer and Singer (1987). These types of deposits have been recognized in the region south of the wilderness study area (Rytuba, 1989). The presence of opal among altered-basalt outcrops in the Tenmile Ridge area and the presence of mercury in a prospect 4 miles southwest of the study area (Figure 1) are additional favorable indicators of hot-spring-type gold-silver deposits.

The Diablo Mountain Wilderness Study Area has no identified resources but does have moderate mineral resource potential for soda ash, boron compounds, sodium sulfate, magnesium compounds, salts, and other brine compounds. Limestone and magnesium from dolomitic limestone in the area of Tenmile Ridge is possible in conjunction with brine resources. The area also has low mineral resource potential for gold, silver, magnesium, and for oil and gas (Fouch, 1982; 1983).

### MINERAL RESOURCES AND RESOURCE POTENTIAL

No mineral resources have been identified within or adjacent to the study area, but brines within lake and playa sediments, sampled from shallow auger holes, contain concentrations of chemical components suitable for the production of soda ash, boron compounds, and sodium sulfate. Possible by-products include potash, salts, bromine, lithium, magnesium compounds, and tungsten. Limestone from the study area could be used in recovering soda ash, boron compounds, sodium sulfate and magnesium compounds from brine.

The area includes thermal springs and lies 2 miles south of the Summer Lake Known Geothermal Resource Area (KGRA). Thermal resources from the area may be useful for power production by the binary method through the use of a low-boiling medium, as well as agricultural and building heating. Thermal springs at Ana Springs and Summer Lake Hot Spring are near the study area, and two known thermal-water springs were observed within the study area.

A low mineral resource potential in the area of Tenmile Ridge for low-grade, high-tonnage epithermal hot-spring gold-silver deposits is suggested by the presence of opal in some altered-basalt outcrops and by the presence of mercury in a nearby prospect. The mineral resource potential is low for magnesium from dolomitic limestone in the area of Tenmile Ridge. Oil and gas resource potential is low throughout the study area.

### MINING AND MINERAL EXPLORATION HISTORY

Lake County mining records indicate that the Oregon Prospect (claims group, Figure 2), a large block of 326 placer claims, was located in 1901 by an eight-person-association and was relocated by the same claimants in 1906 (Lake County mining records). The claims group extended from 2 miles north to 1 mile south of Summer Lake and as much as 2 miles east and 1 mile

west; it included the entire lake and surrounding playa. The discovery, according to Lake County mining records, was for "... the valuable metals, sodium and potassium and their compounds of bicarbonate of soda, carbonate of soda and potassium sulfate, in paying quantities held in solution and in deposit, ..." The claimants were Charles M. Sain, John T. Reid, Schuyler Duryee, W.F. Brock, and William, Charles, Canby, and Elwood Balderston. The eastern part of the Oregon claims group extended into the western part of the study area. The claim block boundary extended north-south along the western part of the study area.

With the outbreak of World War I, foreign potash supplies were cut off and the price increased from \$0.80 to \$8.00 per 20-pound unit. In 1916, the first successful plants to produce potash and other evaporite minerals from brine came on line at Searles Lake, California (Teeple, 1929). On December 16, 1914, the state of Oregon leased the mineral rights to soda salts in Abert and Summer Lake on a royalty basis (Hartley, 1915). Ambitious development plans included a 270-mile pipeline north to the Columbia River and a large hydroelectric plant; an investment of about \$7,000,000 (Phalen, 1916, p. 107-108). Outside, but adjacent to the south boundary of the study area (Figure 3), are remnants of a water retention levee and an evaporation pond. These were apparently developed in 1918; John Withers, a local rancher, recalls that much money and effort was spent that year by a crew of men led by Jason Moore. After the armistice, the potash price dropped and by mid-1919 was at \$1.75 to \$2.00 per 20-lb unit. Perhaps this was the main reason for not continuing the work at Summer Lake.

In March 1974, a group of claims including the Tenmile Prospect and six others were located for limestone on the northeast side of Tenmile Ridge. Claimants included Harold J., and Marie Dyke of Adel, Oregon, Frances M. Foster, Con O'Keefe, Laura Shine, Jerry and Julia Singleton, and Morgan Verling. John Cremin (Lakeview, Oregon) examined the prospect in 1980, brought it to the attention of the authors, and reported that exposures of the limestone extend into the study area.

## THE OREGON PROSPECT

The Oregon claims group, inactive since 1918, covered all of Summer Lake, including the west margin of the Diablo Mountain Wilderness Study Area (Figure 3). The prospect was primarily for brines; no conventionally mineable beds of evaporite minerals are known. Summer Lake waters are not sufficiently concentrated to be a source of resource-bearing brine. In 1969, the lake, with a maximum water depth of about 3 feet, contained a calculated total of only 1 million tons of mineral salts;

however, the top 5 feet of lake-bottom and margin sediments contained 15 to 20 million tons of evaporite minerals. The greatest quantities of evaporite minerals are under the eastern playa rather than under the lake (Van Denburgh, 1975). Seasonal variation of fresh water and evaporation renders the solute concentration too inconsistent for the lake waters to constitute a brine source for year-round processing. Interstitial brines sampled from auger holes (Peters and Willett, 1989, tables A-1 and A-2) are much higher in solutes than the lake-water samples reported by Van Denburgh (1975, Table 4).

Within the study area, brine-hosting lake and playa sediments define a mineral area extending more than 10 miles east of the claims group. Much of this area has a veneer of windblown sand as much as several tens of feet thick. Several flat-floored blowout basins, displaying white surface efflorescence characteristic of areas underlain by evaporative brine, have formed windows through the sand.

## FIELD METHODS

Samples from 21 hand-auger holes (Figure 4) from within the study area east of Summer Lake are described by Peters and Willett (1989, Plate 1, Tables A-1 and A-2). Samples consist of alkali crust (efflorescence), auger sediment, and, where available, auger-hole brine; several spring and seep samples were also sampled.

Lake and playa sediments are interbedded. Deep auger holes typically were collared in brown silt-, clay-, and fine-sand-sized playa sediments and extended into black silt- and clay-sized lake sediments. Only one evaporite bed, 0.4 feet of halite, was encountered during augering. Several holes ended in coarse, clean, black basaltic beach or stream sand. Permeable beds, along with soluble evaporite beds at depth, are essential for pumping brine from the sediment and recharging them with ground water. Such beds also are needed for recharging the ground water with new mineral salts. Clay-dominated facies that have high brine content may not yield enough brine and contained-evaporite mineral components for commercial exploitation.

Sampling of the mineral area by hand auger yields data on the mineral and brine composition of the top few feet and allows comparison with chemical data from analogous mineral systems that are better understood. An appropriate place for comparison is Searles Lake, California, about 500 miles to the southeast, where evaporite commodities have been extracted from brines and evaporite deposits for more than 50 years (Smith, 1979). Meaningful quantitative resource estimation, however, requires drilling and subsurface sampling.



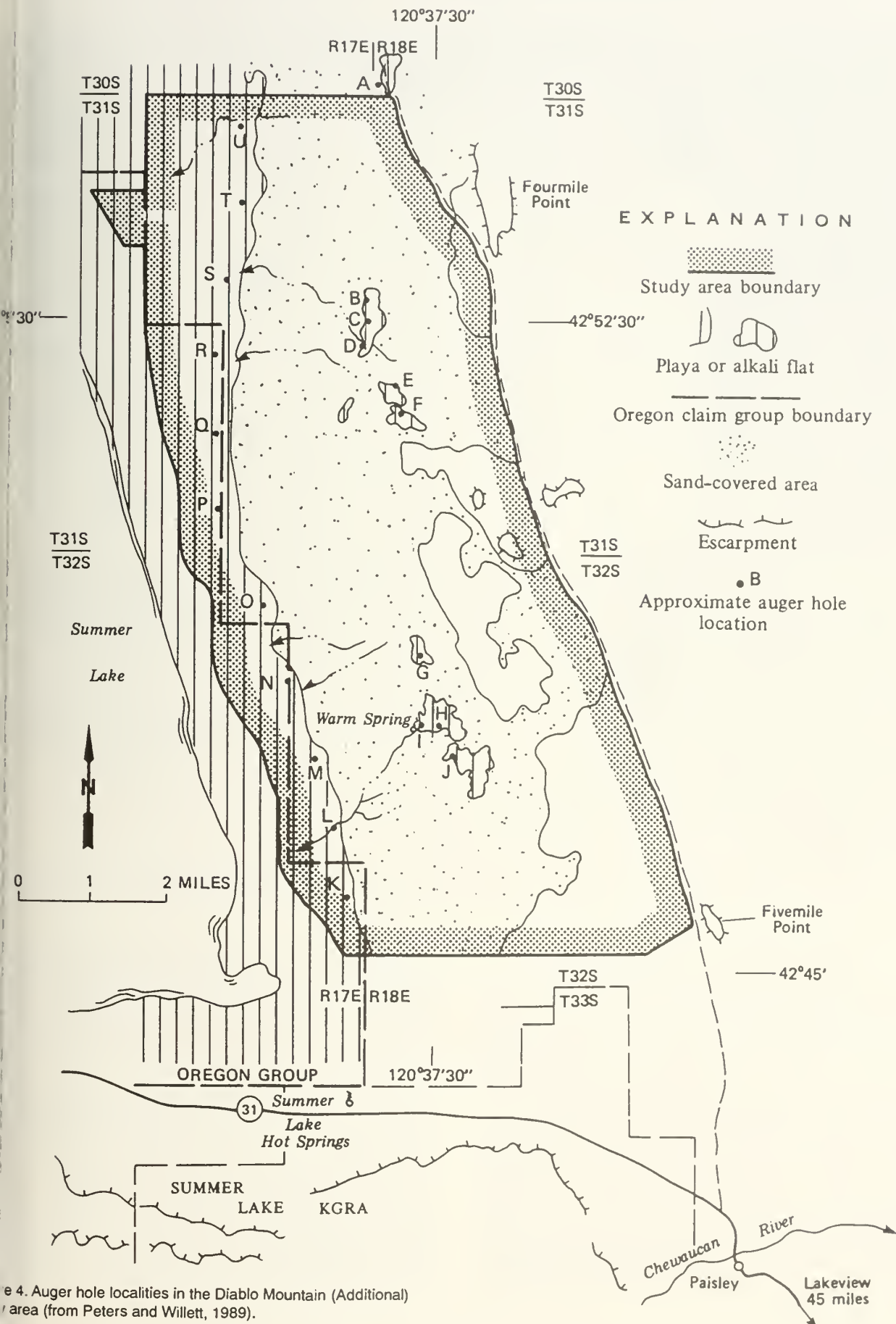


Figure 4. Auger hole localities in the Diablo Mountain (Additional) area (from Peters and Willett, 1989).



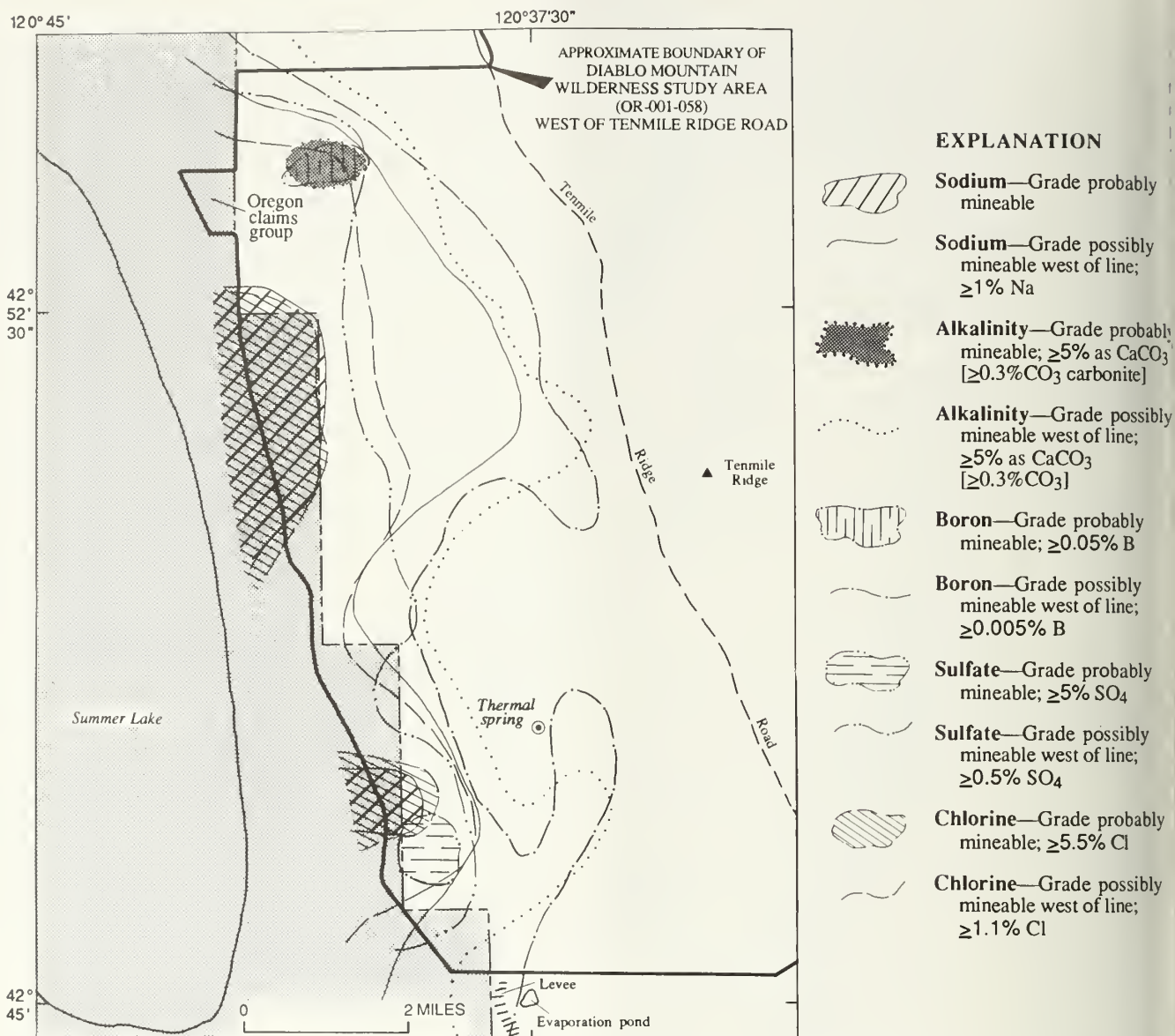


Figure 5. Concentrations of chemical components of brine commodities in ground water in the Diablo Mountain (Additional) study area (from Diggles and others, 1990b).

## Brine Commodity Evaluation

Brine samples were analyzed for cation (+) and anion (−) components of evaporite commodities that include soda ash, boron compounds, sodium sulfate, salts, potash, and lithium. Samples were also analyzed for arsenic and antimony which are not only possible toxic contaminants but are also indicators of nearby epithermal mineralization or mineralizing processes. The auger-hole sediments and alkali crusts were analyzed for major-element oxides and 36 trace elements. Possible products, based on component concentrations and commodity economics, include soda ash (sodium carbonates), boron compounds, and sodium sulfate (Figure 3). Possible by-products include potash, salts, bromine, lith-

ium, magnesium compounds, and tungsten; their production may be feasible in conjunction with other commodities. Processing of many of the products could be facilitated by treating them with dolomitic limestone, which is also present in the study area.

Our brine analyses were compared to published analyses of brines from Searles Lake, California (Smith, 1977, Tables 5, 16, and 22). Ranges of concentration of possible significance now or in the foreseeable future were chosen by using the Searles Lake operation as a guide. Our cutoffs are lower than those for the Searles Lake brine concentrations because: (1) low concentrations in surface samples do not preclude higher concentrations at depth, (2) advances in extractive technology allow utilization

Table 1. Occurrence of brine commodity component in the Diablo Mountain (Additional) Study area, Lake County, Oregon

Auger hole (A-U)	Brine sample no.	Hole depth in ft	Wgt % water (#3)	Alkalinity as CaCO <sub>3</sub> %	Concentration (#4)					
					B+ %	Cl- %	K+ %	Li+ PPM	Na+ %	504-- %
D	28 b	8	21.68	*4.48	*0.0250	0.68	0.100	<0.1	*3.40	0.10
F	31 b	8.4	34.16	*.91	*.0075	*1.30	.022	<.1	*1.30	.27
H	47 b	6	22.46	*.74	*.0063	.50	.022	<.1	.97	.21
J	65 b	5.6	28.44	*1.52	*.0124	.97	.038	<.1	*1.30	*.41
K	69 b	4	29.74	.44	*.0080	.27	.053	2.0	.57	.29
Seep	70 b	n.a.	--	*.66	*.0067	.35	.025	<.1	.69	.39
Seep	71 b	n.a.	--	*.72	*.0059	.33	.017	<.1	.55	.29
L	75 b	4	31.61	*2.63	*.0230	*3.00	.090	<.1	*3.30	**6.90
M	78 b	4	39.97	*2.58	*.0230	**5.70	.110	.3	**5.20	.62
N	81 b	4	34.71	*1.77	*.0140	*1.50	.045	<.1	*1.90	.35
Seep	82 b	n.a.	--	*.75	*.0059	.32	.017	<.1	.59	.16
O	85 b	4	40.44	--	*.0065	--	.053	.9	.68	n.a.
P	88 b	4	36.59	*2.47	*.0250	--	.045	<.1	*4.90	*.58
R	94 b	5.9	42.84	*2.92	*.0390	**5.60	.130	<.1	**5.30	*.60
Seep	97 b	n.a.	--	*1.94	*.0160	*1.30	.032	<.1	*2.00	*.40
T	100 b	4	28.30	**5.43	**0.0500	*2.70	.110	<.1	*4.70	*1.20

Possibly mineable grades are within one order of magnitude of Searles Lake brines (Smith, 1979, Tables 9, 16, and 22), except boron is within two orders of magnitude.

Probably mineable concentrations are equal to, or greater than one half of Searles Lake brines (Smith, 1979), except boron is within one order of magnitude.

Wgt % water - weighted average weight percent water of wet sediment sample from auger hole.

% (percent) multiplied by 10,000 = (equals) mg/L; ppm approximates ml/L.

Concentration possibly mineable, (#1); (\*) grade probably mineable; (n.a.) not applicable; (--) not available; (ppm) parts per million]

over grade brines (Smith, 1979), (3) the advantage of large-scale application of such technology is inherent in designing new facilities, and (4) possible markets may be larger. Two categories of brine commodity occurrence, based on chemical component concentrations, were chosen; a grade that is probably mineable, and a grade that is possibly mineable (Figure 3). Occurrences of probable mineable concentrations are defined as approximately equal to or greater than 50 percent of the grade of Searles Lake brines for all products except boron, which is of higher unit value. The grades of possible minable brines in the study area are equal to or greater than 10 percent of the grade of Searles Lake brines. Boron could possibly be economically mined from lower grade brines than

those at Searles Lake by using advanced technology in new plant design (Gail Moulton, oral communication, 1989). Grades of brine components at least as good as the possible minable grade were observed at 12 auger sites and at 4 seeps (Table 1).

The areal distributions of brine components in the study area for possible mining products were analyzed by plotting isocon maps (contour maps of chemical concentrations) of the sodium, alkalinity (as CaCO<sub>3</sub>), boron, sulfate, and chlorine concentrations (Peters and Willett, 1989, Figures 3-6). Those maps were generalized and combined for this report and areas interpreted to have probable mineable grades are denoted by patterns (Figure 5). Isocons were defined by the kriging method



(Bridges, 1985), and all isocons were smoothed using Golden Software's SURFER software on a Microsoft-DOS-based desktop computer. Isocons of concentrations within brine or in sediment samples were similarly plotted for all by-product components, except tungsten (Peters and Willett, 1989, Figures 7-11). Fourteen additional isocon, specific conductance, and isocon/specific conductance ratio maps were also prepared (Peters and Willett, 1989, Plate 2). Grades of brine components with possible economic significance extended east of the Oregon claims group, but were highest in the claim block vicinity.

## THE TENMILE AND OTHER DOLOMITIC LIMESTONE PROSPECTS

A dolomitic limestone of Pliocene(?) age is locally interbedded with basalt flows at the Tenmile and other dolomitic limestone prospects. It appears to have formed as an apron along the east, northeast, and north flanks of Tenmile Ridge and may extend for 2 miles to the northwest. It crops out discontinuously through a veneer of sand dunes and desert pavement. Four samples of the dolomitic limestone were collected (Peters and Willett, 1989). The rock is suitable for brine mineral processing and agricultural applications. Usually the thickness could not be determined, but Harold Dyke (oral communication, 1988) reports the rock is as thick as 30 feet northeast of Tenmile Ridge. No resources were estimated because of limited exposure.

### Geothermal Energy

One thermal spring was observed in the study area, and thermal water was present in one auger hole (Peters and Willett, 1989). There are no known geothermal resources in the study area; however, the Summer Lake KGRA is 2 miles south of the southern boundary.

## MINERAL ECONOMICS

### Soda Ash

Soda ash (sodium carbonate,  $\text{Na}_2\text{CO}_3$ ) is recovered by North American Chemical Company from brines at Searles Lake by two methods: an older evaporation process, and a direct carbonation process. The evaporation process involves heating the brines, which causes the double salt burkeite ( $\text{Na}_2\text{CO}_3 \cdot 2\text{Na}_2\text{SO}_4$ ) and table salt ( $\text{NaCl}$ ) to precipitate. The remaining liquor is rapidly cooled, and potassium chloride is precipitated and filtered out. The remaining brine is supersaturated with sodium borate, which is precipitated after the addition of "seed" crystals (Gail Moulton, oral communication 1989). In the direct carbonation process, brine is mixed with carbon dioxide ( $\text{CO}_2$ ) gas. At Searles Lake (Parkinson, 1977), carbon dioxide is produced from powerplant flue gases; carbon dioxide has traditionally been produced from lime kilns.

The soda lakes of south-central Oregon are similar appearance and composition to other surface lakes with evaporite crusts and subsurface brines found worldwide. These types of soda deposits provided the crude sodium carbonate used about 3,500 B.C. by the Egyptians to make glass ornaments and containers as well as other medicinal and food-additive applications. Plant ash was first used in Europe and America as a source of alkali and was prepared by burning plants found in salt-bearing soils, seaweed and leaching the residue to obtain "soda ash" (term still used today). However, naturally occurring soda precipitate found in many surface evaporite deposits was preferred.

The first commercial soda ash operation in the United States was in 1868 at Little Soda Lake at Ragtown, Nevada, near the present town of Fallon. Workers excavated the evaporated crude sodium carbonate found along the margin of the lake. Imports of soda ash from Europe supplemented the soda alkali needed for glass and detergent manufacturing. Although the Leblanc process that originated in France produced an impure soda ash, it was not until the 1860s when a technique to make synthetic soda ash was developed. Because the continued use of burning seaweed and plants became economically impractical and supplies were becoming more scarce, synthetic soda ash production increased throughout the world. In addition, because trona (the primary ore of soda ash) and some of the other carbonate-bearing minerals are water soluble, there are not very many economic surface deposits found in the world despite the numerous occurrences of sodium carbonate commonly associated with many evaporite resources.

The birth of modern natural soda ash production began in California in 1887 at Owens Lake and was further developed in 1931 at Searles Lake. It started in Wyoming in 1948 at Green River. Because the location of these deposits was in the west, the majority of the market tended to be within that region. The remainder of the nation used synthetic soda ash, which was first produced in the United States at Syracuse, New York. At one time there were ten synthetic plants operating in the northeast, east, southern Gulf Coast, and upper Midwest. The rivalry between natural and synthetic soda ash continued for many years. Because world production capacity was adequate to meet demand, the United States exported very little soda ash prior to 1970.

During 1987 soda ash was produced by five companies operating five plants in Wyoming, and by one company operating two plants in California; total estimated value was \$837 million. Industrial use of soda ash was the following proportions: glass, 48 percent; chemicals, 24 percent; soap and detergents, 13 percent; distributed,



percent; flue gas desulfurization, 3 percent; pulp and paper, 2 percent; water treatment, 2 percent; and other, 1 percent (D.S. Kostick, in U.S. Bureau of Mines, 1993, p. 162). In 1992, the United States exported 3.3 million tons of soda ash; a total of 43 percent went to all Asian countries, the largest export market.

## Boron Compounds

Generalized boron concentrations of the brines in the study area are shown on Figure 5. Processing these brines probably would be similar to extraction methods at Searles Lake, California, where brines containing boron are mixed with a liquid extractant that removes boron from the brine. Boron is then purged from the extractant with sulfuric acid, and used to produce boric acid  $[B(OH)_3]$ . Sodium and potassium sulfate remain in the liquor and can be recovered.

Boron, though unfamiliar to most people, has many uses. Borates have been used as a flux in metal smithing since their introduction into Italy from Mongolia in the 13th Century, and they were used to add strength to glass made by medieval European artisans. Elemental boron was first isolated in 1808. The boron mineral tincal ( $Na_2B_4O_7 \cdot 10H_2O$ ) was discovered at Teel's Marsh, Nevada, in 1872 and ulexite ( $NaCaB_5O_9 \cdot 8H_2O$ ) was discovered in Death Valley, California, in 1881. By 1927, underground mining of a massive tincal and kernite ( $CaB_4O_7 \cdot 4H_2O$ ) deposit had begun at Boron, California. Mining was converted to open pit methods in 1957. U.S. Borax annually produces about one-half of the world's boron from these deposits. North America produces boron compounds as a co-product of solution mining of soda ash at Searles Lake (Trona, California). For further detail about the boron industry, see P.A. Lyday in U.S. Bureau of Mines (1985, p. 91-102). The United States is currently the largest producer of boron compounds (P.A. Lyday, in U.S. Bureau of Mines, 1993, p. 36-37).

Of the boron compounds produced, 62 percent are used in glass making, 9 percent in soaps and detergents, 10 percent in fire retardants, and 24 percent in other uses (P.A. Lyday, in U.S. Bureau of Mines, 1993, p. 36). Silicate glass withstands severe temperature changes without cracking. Borate compounds are used as metal cleaners and fluxes in the metals industry, as both herbicides and plant nutrients in agriculture, in fire retardants, in heat-resistant ceramic products such as tiles that protect the Space Shuttle from the heat of reentry. Elemental boron fibers are used with tungsten-steel alloys for high strength in helicopter rotors; boron nitride approaches the hardness of diamond and is more heat resistant. Sodium borohydride is used in the bleaching of wood (Rex McKee, oral communication, 1989), and there are many additional applications for boron compounds.

## Sodium Sulfate

Sodium sulfate occurs as two economically important minerals; mirabilite or Glauber's salt ( $Na_2SO_4 \cdot 10H_2O$ ), and thenardite (anhydrous  $Na_2SO_4$ ). Almost all commercial deposits are lacustrine evaporites (W.I. Weisman and C.W. Tandy, in Lefond, 1975, p. 1081-1082). Sodium sulfate can be extracted from brine as a co-product of soda ash and boron compounds. Only about 48 percent of sodium sulfate comes from natural sources; most is manufactured as a by-product of chemical and rayon factories. End uses are in soap and detergents, 44 percent; pulp and paper, 24 percent; textiles, 16 percent; glass, 5 percent; and miscellaneous uses, 11 percent (Kostic, in U.S. Bureau of Mines, 1993, p. 162). The study area is closer to pulp and paper markets in the northwestern states than are current sources of sodium sulfate.

## By-Product Brine Commodities

Production of six by-product commodities, table salt ( $NaCl$ ), potash ( $K_2O$ ) and muriate of potash ( $KCl$ ), bromine, lithium, magnesium compounds, and tungsten from the study area may be feasible. By-product salts are produced at Searles Lake, and two companies in Portland, Oregon, currently buy imported Mexican salts for the manufacture of caustic soda and chlorine compounds. It may be economical to recover magnesium compounds from the site of the Oregon claims group. A local source of dolomitic limestone to be used in processing the brines would make additional magnesium available for by-product compounds. The additional investment needed to extract by-products from a resource-producing brine, even at low concentration, may be somewhat small. Distribution of by-product concentrations and uses are discussed in more detail by Peters and Willett (1989).

## Dolomitic Limestone

The dolomitic limestone occurrence along Tenmile Ridge may be useful for its possible application in brine commodity processing. Carbon dioxide produced from the calcination of limestone or dolomite is used to remove calcium from brines, thus allowing further separation of soda ash, boron compounds, and sodium sulfate. A calcination by-product, calcium hydroxide, can then be used to convert soluble magnesium salts into insoluble magnesium hydroxide, which in turn can be calcined to produce magnesia. Another proposed use of the limestone is as a soil conditioner; this may be feasible if there is enough limestone and if low-cost rail transportation is available in conjunction with development of other mineral commodities.

## GEOHERMAL ENERGY

Summer Lake Hot Spring (Figure 2) produces 116°F water at a rate of 21 gallons per minute (Peterson and McIntyre, 1970) and is developed as a resort. The presence of the thermal spring, in part, resulted in the designation of the Summer Lake KGRA, which includes three additional geothermally significant wells (Oregon Department of Geology and Mineral Industries, 1982, wells Lk-7-10). Of special interest are the Collahan wells Lk-9 and Lk-10, which have water temperatures of 212°F and 231°F, respectively, but do not produce dry steam, the most efficient medium for electric power generation. However, water temperature at Summer Lake KGRA is much higher than the 100°F minimum needed for power production by the binary systems process (Rinehart, 1980). The brines at these thermal springs are also possible metal sources (Schultze and Bauer, 1975; Blake, 1974).

## CONCLUSIONS REGARDING THE OREGON PROSPECT

Brines, sampled from shallow auger holes, host occurrences of the chemical components of soda ash, boron compounds, and sodium sulfate, which may be extracted by solution mining. By-product candidates include potash, salts, bromine, lithium, magnesium compounds, and tungsten. The sample data suggest solution-mineable resources, but resource estimates will require drilling for estimates. Limestone from the study area could be used in recovering soda ash, boron, and magnesium compounds from brine, or in agricultural applications. Geothermal energy near the study area could be used to generate electric power.

## MARKETS AND TRENDS

Of the 10.4 million short tons of domestic soda ash produced in 1992, 3.3 million tons was exported to 51 countries throughout the world (Figure 6). The soda ash was used to manufacture glass bottles, window glass, soaps and detergents, and various inorganic chemicals.

The United States is the world's largest producer of soda ash, comprising about one-third of total world output. The majority of the world's production is synthetic soda ash, made by using salt and limestone as feedstocks. Synthetic soda ash is more expensive to manufacture than natural soda ash. It also generates more pollution and is very labor intensive. Because of the higher cost of synthetic soda ash, exports of U.S. soda ash are expected to increase throughout the remainder of the decade.

The emergence of the United States as a soda ash exporter had its roots in two important events in the early 1970s. These were the Arab oil embargo in October 1973

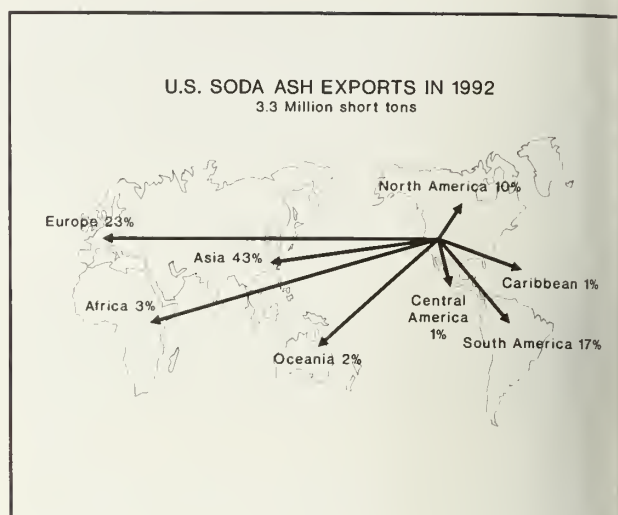


Figure 6

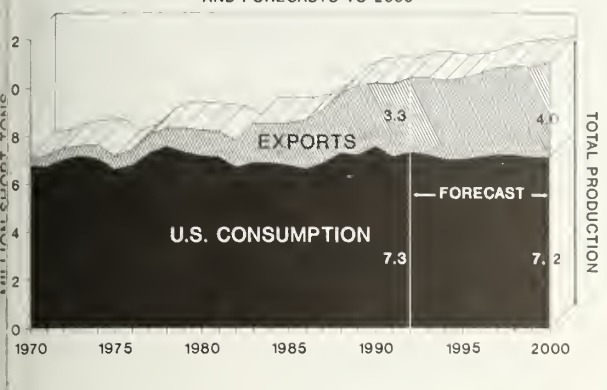
that caused fuel prices to soar, and the ecology movement within the United States that prompted antipollution legislation to be enacted. Synthetic soda ash requires about twice the amount of energy to produce a ton of soda ash compared with the fuel requirements to produce a ton of natural soda ash. The synthetic process also generated by-product sodium chloride and calcium chloride, both of which were usually discharged as waste effluents by plants and were considered detrimental to the environment. Of the ten synthetic plants that were constructed in the nation, seven were in operation when the energy and environmental problems emerged in 1973; by year-end 1979, only one remained in production. Ironically, it was the Syracuse plant which was the first one built in the United States. This plant finally ceased operation in 1992, ending the era of synthetic U.S. soda ash production.

The energy and environmental issues that led to the demise of the U.S. synthetic soda ash industry began to surface in Europe and elsewhere in the world in the early-to-mid 1980s. The "Green Movement" in Europe identified some of the synthetic plants as contributors to Europe's air and water pollution, which forced less economically sound plants in Czechoslovakia, England, France and Switzerland to close. A similar situation occurred in Asia and South America. Foreign glass and chemical manufacturers wanted to obtain less expensive soda ash, and the United States began to increase exports to these markets.

By 1982, five companies in Wyoming and one in California were exporting 14 percent of domestic output (Figure 7). The industry formed the American Natural Soda Ash Corporation (ANSAC) to promote export sales, and the industry was able to ship natural soda ash more efficiently. From 1970 through 1992, U.S. apparent consumption increased 6 percent, while exports rose dramatically 869 percent.



**U.S. SODA ASH TRENDS**  
**U.S. CONSUMPTION VERSUS EXPORTS**  
 1970 - 1992  
 AND FORECASTS TO 2000



Soda ash and a daughter product, caustic soda, and sodium borohydride have received increased use in bleaching wood pulp. At present, most pulping is done using an alkali process, only a few older mills and specialty mills use an acid process. Most paper bleaching is still done using the Kraft process, which produces chlorinated wood wastes that can evolve into dioxin, and chloroform waste that is disposed of through smoke stacks. The next several years will see a complete transfer to alkali bleaching, which will use large tonnages of caustic soda from a soda ash source through a modified Solvay process (Jerry Gess, 1993, oral communication). The new process will be more energy efficient, and many chemicals will be recovered from waste products.

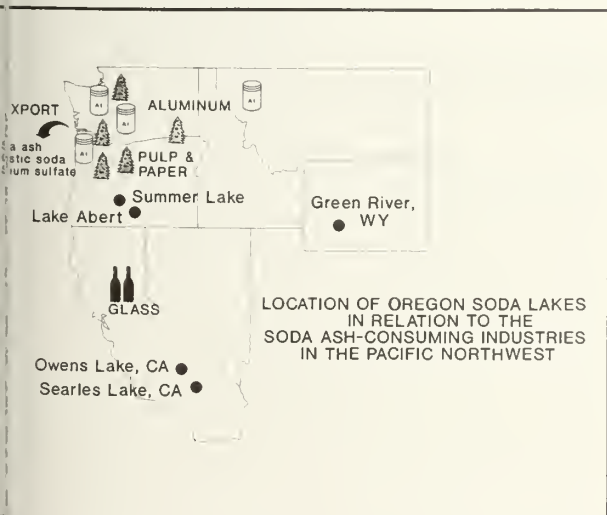
Alkali bleaching is ecologically preferable to the current acid processes that use chlorine compounds, and produces a carcinogenic dioxin waste product. Soda ash, soda-ash products, and boric acid are widely used in fluxing metals and are used in the aluminum industry in the Pacific Northwest and in developing Pacific Rim countries. Evaporite commodities are essential to the backbone industries of many civilizations and to many new applications and advanced materials.

With regard to the Oregon prospect, bulk commodity transport by railroad is available from Lakeview, Oregon, 45 highway miles to the southeast. There are no weight restrictions on the 55-mile-long Great Western Railroad shortline from Lakeview to Alturas, California; rail distance from Alturas to Portland, Oregon, is 415 miles. Railroad infrastructure could be extended from Lakeview to a new mine site for about \$200,000 per mile (land not included) (Edward Emmel, Oregon Department of Transportation, Salem, oral communication, 1989), possibly in conjunction with other bulk product development such as perlite from the Tucker Hill deposit, 14 miles southeast of the study area (Wilson and Emmons, 1985). In this scenario, brine minerals could be shipped directly by rail to Portland a total distance of about 520 miles; this distance represents 55 percent of the 912-mile-long rail distance between Portland and the premier trona producing area, the Green River District in southwest Wyoming.

Although soda ash is currently produced in the United States by five companies in Wyoming and by one in California (with another in the pre-development stage at Owens Lake), the Oregon soda lakes may become an important soda ash consuming industry in the Pacific Northwest. The lakes are also within the range of some of the glass container plants of northern California, as well as Portland port facilities that handled about 60 percent of the U.S. soda ash export business.

## THE PACIFIC NORTHWEST

Markets for brine-mineral products appear to be undergoing steady growth, especially in the Pacific Northwest (Figure 8) and in Pacific Rim countries. Soda ash, also known as sodium carbonate, is the third largest inorganic chemical in terms of volume produced in the United States. It is obtained domestically by processing trona ore from the world's largest deposit in Green River, Wyoming, or from underground sodium carbonate-bearing brines found near Searles Lake, California. Other sodium carbonate deposits, such as those in Summer Lake and Lake Abert in Oregon, are potentially important.





## THE PACIFIC RIM

The Pacific Rim represents an important region for U.S. soda ash exports. In 1992, 60 percent of total export sales was to this area, including Canada and Mexico (5 percent each; Figure 9). Asia was the primary destination of U.S. soda ash exports, representing 43 percent of total foreign shipments. Japan and the Republic of Korea were the major importers in 1992. Some of the Pacific Rim countries, such as Australia, Japan, and the Republic of Korea, produced synthetic soda ash, which competed with U.S. exports. In 1987, partial or total foreign acqui-

sition of U.S. producers began to occur. Foreign soda ash companies experiencing the higher operating economies of running synthetic operations saw the advantages of producing from natural resources in the United States.

Japanese and Korean companies are now joint venture partners with three of the U.S. soda ash companies. Japan's TOSOH Corp. and Asahi Glass Co. own 24 percent and 20 percent, respectively, of General Chemical and Sovay Minerals, respectively, in Green River, Wyoming. Oriental Chemical Industries of Korea owns a 27 percent share of North American Chemical Co. in California. Total

foreign ownership of the U.S. soda ash industry stands at 49.4 percent. Only one of the companies is exclusively U.S.-owned—FMC Wyoming Corp.

As the demand for consumer products increases in many of the nations of the Pacific Rim, which have burgeoning populations and rapidly developing economies, the long-term outlook for soda ash supplied by the United States is very favorable. The region has been very important to the U.S. soda ash industry and will continue to be so into the 21st century.

The soda lakes of Oregon have the potential to supply a portion of the soda ash demand in the Pacific Northwest, and possibly supply a portion of the soda ash, or value-added soda ash products, for export. More physical and economic evaluation of the Oregon soda lakes will be needed to determine the potential of the occurrences.

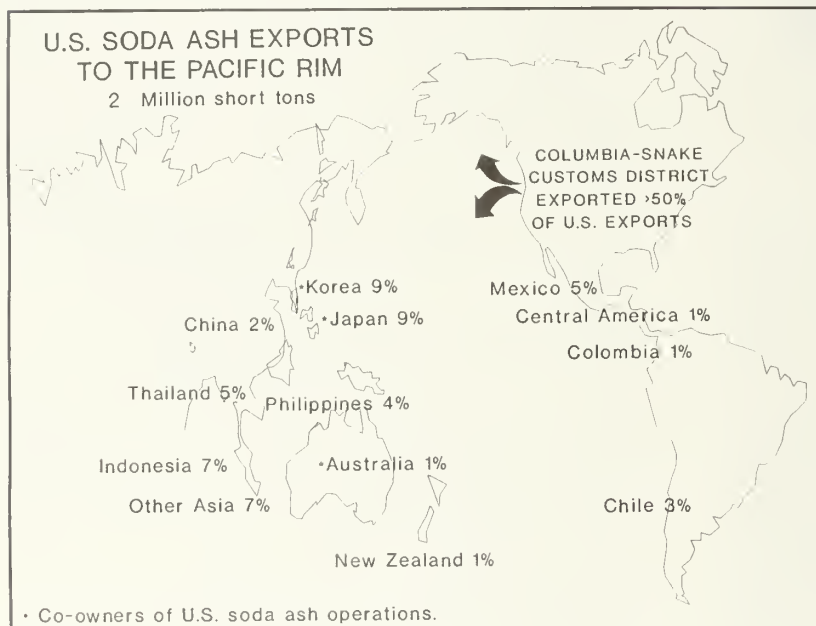


Figure 9

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## 30th Forum on the Geology of Industrial Minerals: Nova Scotia/New Brunswick, Canada

by

John H. Fowler<sup>1</sup> and Timothy C. Webb<sup>2</sup>

The 30th Forum on the Geology of Industrial Minerals will be held in the historical seaside city of Halifax, Nova Scotia, from May 22 to May 27, 1994. The Forum will be co-hosted by the Provinces of New Brunswick and Nova Scotia, two of Canada's East Coast Provinces, both having a long tradition of industrial mineral production.

Two previous Forums, the 19th in Toronto in 1983 and the 27th in Banff in 1991, offered delegates the opportunity to see industrial minerals in central and eastern Canada. The 30th Forum will take you to Canada's east coast completing the picture of Canada's industrial minerals from coast to coast.

Both New Brunswick and Nova Scotia's 200-year history of producing and shipping industrial minerals is a result of these Provinces' success in combining the prerequisites for successful worldwide marketing - abundant reserves and strategic location for export trading.

Aggregates, clay and shale, limestone and dolomite, building stone, salt, peat moss and silica are produced in both New Brunswick and Nova Scotia, but each Province contributes significantly to Canada's production of potash and gypsum. New Brunswick is one of only two potash-producing provinces in Canada and Nova Scotia is one of the largest gypsum producing regions in the world. The 1992 preliminary estimated value of industrial mineral production in New Brunswick was \$285,000,000 with employment in the industry at 1000 persons. In Nova Scotia the estimated value of industrial mineral produc-

tion for the same year was \$205,000,000 with 1800 employees. Major markets for many of the industrial minerals produced in New Brunswick and Nova Scotia are the United States, South America, Western Europe, and Japan.

Comparable to previous Forums, there are to be 2 1/2 days of technical sessions and 3 days of field excursions to industrial mineral developments in southern New Brunswick and eastern Nova Scotia. For the benefit of the Forum's field trip participants, a special pre-meeting excursion is planned for New Brunswick. Participants and their guests will assemble in Fredericton, New Brunswick's lovely elm-shaded capital city, on the evening of May 21 for a welcoming reception. We will depart the following day for the small town of Sussex, a short drive to the south. This area offers a diverse assortment of atypical industrial mineral operations that are certain to accommodate various interests.

While in the Sussex area, it is our intention to offer a few field trip options. The first will involve an underground and surface tour of the Potash Company of America's (PCA) operation, one of New Brunswick's two potash mine/mill facilities. PCA's integrated approach to mining, processing, and tails disposal is unique to North America, if not the world. Approximately 2 million tonnes of potash ore and 0.5 million tonnes of salt are mined and processed annually. Close to 1.5 million tonnes of salt tailings from the milling process and rock salt screening operations are sent directly back to active cut-and-fill

potash stopes to be used as backfill. Clay slimes and excess brine slurries from the mill are piped underground to be discharged into large rooms created by the mining of rock salt. As the slimes settle out, the resulting brines are pumped back to surface for input into an evaporation process, which recovers remnant potash contained in the brine. The entire process results in a closed circuit or "zero effluent" operation, something which is particularly appealing in view of the present level of concern over the environment.

Option two will feature a visit to Havelock Lime, the largest producer limestone and quicklime and hydrated lime in Atlantic Canada, and to Kent Peat Moss Ltd., one of New Brunswick's numerous peat moss operations. Of particular interest at Havelock Lime is the company's efforts to improve product quality and operational efficiencies. For instance the installation of a fuel efficient Fuller Beckenbach vertical shaft kiln, considered to be among the first of its kind operating in North America, and a new hydrator has had a significant positive impact on the production of quicklime and hydrated lime. Other interesting operational modifications have also enhanced product quality and reduced materials handling and related production costs.

Kent Peat Moss is one of several companies producing various horticultural peat products in the Province. Total Canadian peat production ranks third in the world after the CIS and Germany. New Brunswick is the Nation's number one producer of peat products accounting for 40 percent of its annual output. The Province possesses some of the highest quality sphagnum peat moss in the world. Of particular interest to participants on our peat excursion will be some of the unusual machinery employed in mining this important resource.

A possible third field option is also being considered. It would involve a call on Nelson Monuments Ltd., a major dimension stone processing facility in Atlantic Canada and will feature one of the largest computerized, circular diamond saws in our part of the world.

Sussex Silica Inc. will provide another interesting component of this particular excursion. Some consider this unusual deposit of unconsolidated quartzose sand and gravel and kaolin to be among the largest of its type currently under development in eastern North America. A panoramic view of New Brunswick's largest potash mining operation, the Potacan Mining Company, will also be included in this option.

During our New Brunswick field trip program, guests of the Forum will enjoy a special day trip. A number of tour possibilities exist, including: nature's curious "flower pots" at Hopewell Cape, near Moncton; a visit to the "Bird-

watching mecca of Atlantic Canada" - the Sackville War fowl Park, with lunch at the famous Marshland's Inn at Sackville, and perhaps a short visit at a fort where Britain and France once crossed swords.

"New Brunswick" day will end in Halifax, Nova Scotia, the site of Forum '94's technical program and related social activities. At this point, I'll pass the torch to my Nova Scotia associate and friend, John Fowler. John will talk about some of the interesting things we are planning during your Nova Scotia visit.

Halifax, Nova Scotia, will be the headquarters for Forum '94. It has been referred to as the International Gateway to Atlantic Canada and is the region's largest urban centre. The city is a gentle mix of the old and new - the dynamic and traditional. Founded in 1749, Halifax has developed around a fortified citadel that has been restored to its appearance during the 1800s. Halifax today is Nova Scotia's centre of commerce and government.

The beautiful World Trade and Convention Centre will be the site of Forum '94's technical program. The adjoining Prince George Hotel provides excellent accommodations and related facilities at reasonable convention rates for Forum participants. The hotel is centrally located, just steps away from the bustling harbour front, top-notch shopping, and variety of fine restaurants offering some of the best seafood anywhere.

While in Halifax, city walking tours, an excursion to the Maritime Museum of the Atlantic, or shopping at the harbour front "Historic Properties" should provide interesting pastimes for Forum delegates and their guests. Day trips to Peggys Cove, one of the most delightful - and most photographed - places in Canada, and to the Annapolis Valley to see the apple blossoms as well as a visit to local vineyards may be of interest. Scenic Halifax Harbour cruises are another possibility.

On May 26, the Nova Scotia leg of the field trip program will begin. It will be a 2-day excursion to eastern mainland Nova Scotia and Cape Breton with an overnight stay at Baddeck.

The first stop is National Gypsum (Canada) Limited gypsum quarry at East Milford which is the most productive gypsum quarry in the world. Since it was opened in 1955, production has exceeded 70 Mt and reserves appear to be sufficient to continue mining at this site for the foreseeable future. The gypsum from this operation is moved by unit train (three trains per day) to Halifax Harbour where it is loaded on ocean-going vessels and shipped to markets in central Canada and the eastern United States from Portsmouth, New Hampshire, to New Orleans, Louisiana.

The next two stops are at the Strait of Canso, one of the world's deepest, all weather ports. First, we will visit Construction Aggregates Limited granite aggregate quarry at Auld Cove. Construction Aggregates Limited is a wholly-owned subsidiary of Lone Star Industries Inc. Most of the production from this 2 million tonnes per year quarry is shipped to markets along the eastern seaboard of the United States. Next we will visit the recently completed FiberBond fiber gypsum wallboard plant at Point Tupper owned by Louisiana-Pacific Canada Limited. FiberBond panels are manufactured by blending cellulose fibre and gypsum throughout the panel, not just on the surface, resulting in a strong, impact-resistant panel.

Our overnight stay will be the picturesque village of Baddeck situated on the Bras d'Or Lakes and home of the Alexander Graham Bell Museum. We are planning to attend a performance of highland dancing and Scottish music while in Baddeck.

The second day will take us to The Canadian Salt Company Limited underground salt mine and plant at

Pugwash which is situated on the warm waters of Northumberland Strait. This visit affords an opportunity to examine the internal structures, sedimentology and stratigraphy of a complex diapiric evaporite deposit. This operation, which is a subsidiary of Morton International Inc. of Chicago, employs a non-grid room and pillar method to retrieve the salt which is crushed underground and taken to the surface where additional crushing and screening to remove the anhydrite take place. Fines generated at the mill are taken to an evaporation plant for dissolution and production of pure fine salt.

After our tour of The Canadian Salt operation we will travel along the Malagash Peninsula to Jost Vineyards Limited vineyard and winery for a tour of the winemaking operation. We will then return to Halifax.

The proposed outline should make for an informative and entertaining meeting, maximizing the opportunity for Forum '94 participants to observe a number of selected industrial mineral activities and various cultural venues in both Provinces while minimizing travel times between points of interest.







# Wollastonite in Québec Province, Canada

by

Claude Hébert<sup>1</sup> and Henri-Louis Jacob<sup>1</sup>

## ABSTRACT

The Grenville structural province, a 400 km-wide belt of Precambrian metamorphic rocks which crosses the province of Québec in a northeasterly direction, is the host of several wollastonite occurrences. Most of these are found in marble and calc-silicate rocks enclosed within or located near intrusive bodies. Reconnaissance and detailed mapping of such zones have helped to identify areas of interest for wollastonite exploration.

The most important zone is located in the huge Lake Saint-Jean anorthosite massif in the central part of the Grenville. A recent geological mapping project has revealed the presence of wollastonite in metasedimentary faulted remnant of the roof. The main occurrence consists of diopside and wollastonite in a zone at least 3 km long and 150 m wide. Preliminary sampling suggests an average grade of 50 percent wollastonite with an aspect ratio of 15:1.

Other wollastonite deposits occur in the western part of the Grenville, mainly north and west of Montréal, where the Morin anorthositic complex and a large syenite mass intrude the metasedimentary rocks of the Grenville Supergroup. Marble bands with up to 70 percent wollastonite occur locally at the southern margin of the complex or as an inclusion in the syenite.

Significant wollastonite occurrences have recently been found in the eastern part of the Grenville. One of them is located in metamorphosed calcareous rocks which are part of the granulite facies Manicouagan metamorphic complex. A representative sample analyzed 54 percent wollastonite. Farther south, an inclusion diopside-wollastonite gneiss containing an estimated 40 percent wollastonite occurs at the margin of the Pentecôte River anorthositic complex.

## INTRODUCTION

The Québec part of the Grenville structural province of the Canadian Shield is the host of many wollastonite occurrences.

Even if the potential of the Grenville for wollastonite has been recognized for many years, it was not before the 1930's that surveys were carried out by the Québec Department of Natural Resources specifically to evaluate these occurrences and to check the potential of some particularly favorable environments. More than one hundred occurrences have been documented in the course of these studies, mostly in the Montréal-Gatineau area in

the southwestern part of the Grenville. Other wollastonite occurrences have been found in the Lake Saint-Jean and the North-Shore areas in the central and the eastern parts of the Grenville respectively.

## GEOLOGICAL CONTEXT

The Grenville structural province is a 400 km wide belt of Precambrian metamorphic and igneous rocks, which stretches over 1800 km mainly on the north side of the St-Lawrence River (Figure 1). This part of the Canadian shield was deformed during the Grenville orogeny (1160-970 Ga). It is made up of a series of southeast dipping crustal sheets, which have been divided into three

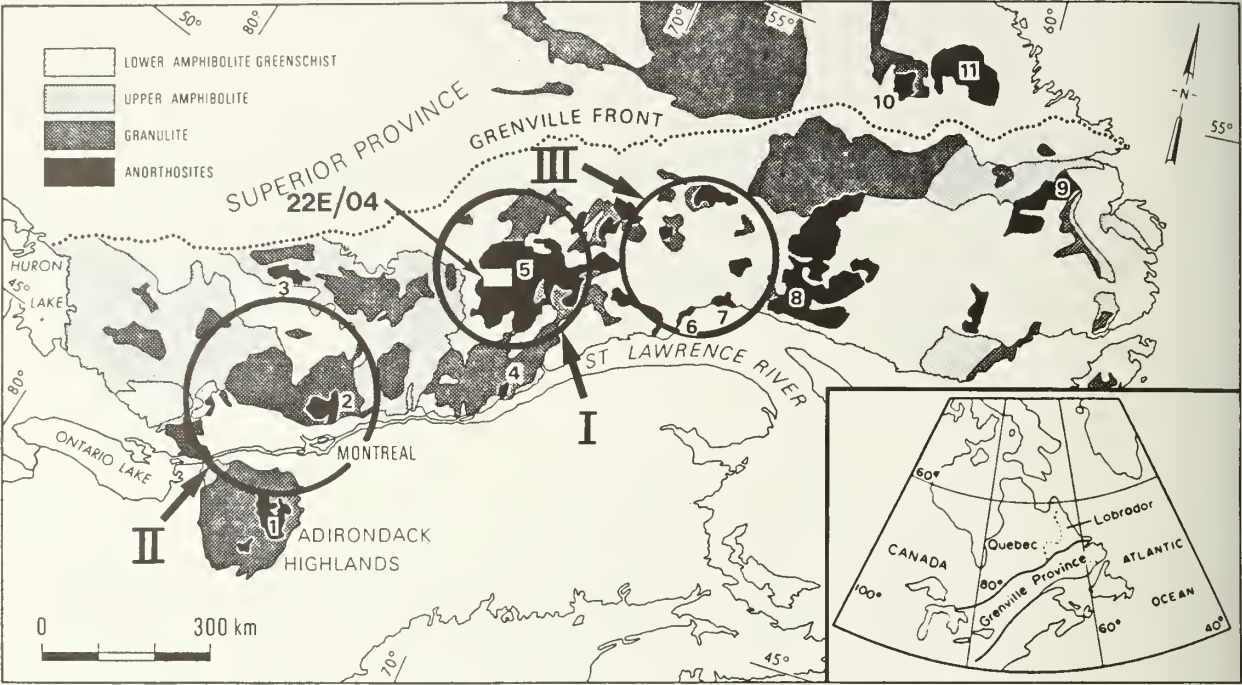


Figure 1. Distribution of anorthosite masses and their relation with metamorphic grade in the Grenville Province (data from Fraser, et al., 1978). 1) Adirondacks; 2) Morin; 3) Lac Bouchette; 4) St. Urbain; 5) Lac St. Jean; 6) Pentecôte; 7) Sept Îles; 8) Havre St. Pierre; 9) Mealy Mountains; 10) Michikamau; 11) Harp Lake. I: Lake Saint-Jean area, II: Montreal-Gatineau area, III: North-Shore area. Modified from Martignole, 1986.

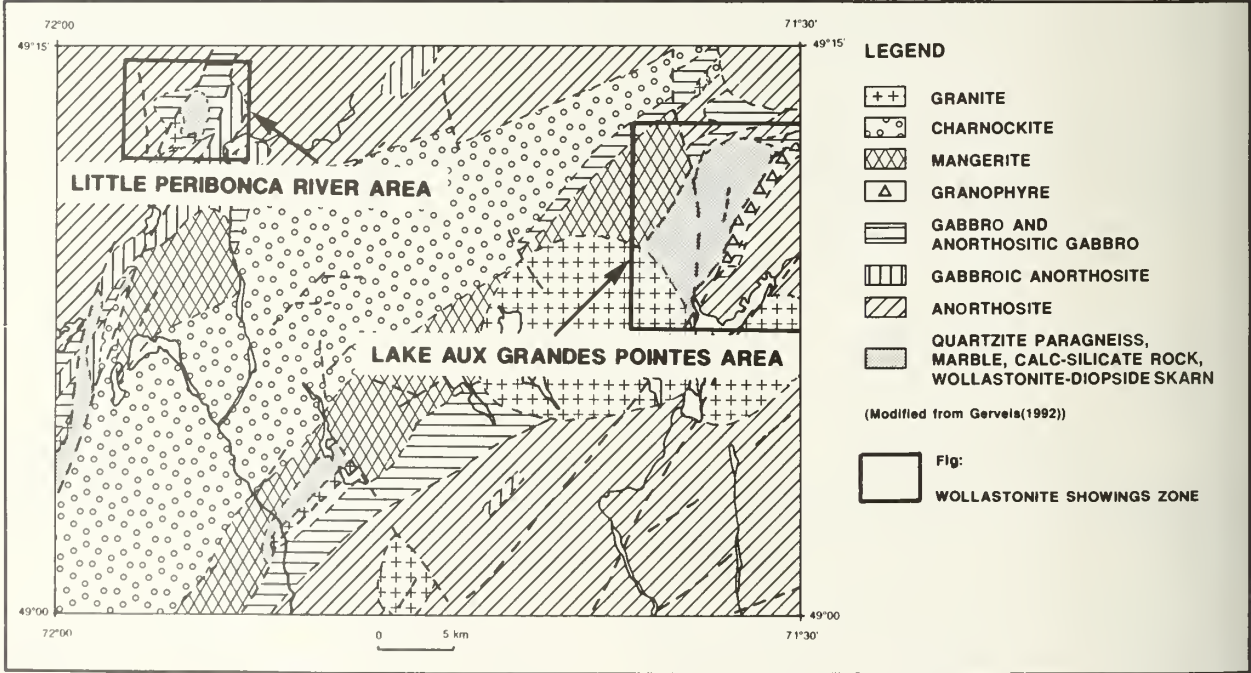


Figure 2. Lake St-Jean area (NTS-22E/04).



or tectonic belts (Rivers et al. 1989). These belts include various lithological assemblages such as: Archean and/or Proterozoic gneisses, metasedimentary rocks, anorthosite masses with genetically or spatially related intrusions, gabbroids, etc., which have been metamorphosed to the upper amphibolite-gabbro facies during the Grenville orogeny.

Most of the wollastonite occurrences are found within metasedimentary rocks (marble or calc-silicate rocks) that occur near or are enclosed in intrusive rocks (mainly anorthosite and related rocks). Such favorable environments are widespread within the Grenville, as we will see in the following descriptions of three important wollastonite occurrences.

### Lake Saint-Jean area

The Lake Saint-Jean area is located in the southeastern part of the huge Lake Saint-Jean anorthositic complex (Figure 1). In this part of the massif, the anorthosite is cut by a series of granitic, dioritic, mangeritic and syenitic intrusions, and locally contain large metasedimentary faulted remnant of the roof. These metasediments are mainly composed with quartzite, dolomitic or calcitic marbles and calc-silicate rocks. Five metasedimentary zones are identified by reconnaissance mapping in 1989 and 1990. Two of them contain significant quantities of wollastonite (Hébert, 1989, Gervais, 1990) (Figure 2).

The main occurrences are in the Lake aux Grandes Pointes zone (Figure 3), where a major wollastonite-skarn zone, 5 to 6 km long and up to 150 m wide, has been mapped. The Lake aux Grandes Pointes skarn is a banded rock formed by the alternation of centimetre scale monomineralic bands of coarsely crystalline white wollastonite and centimetre scale greenish bands composed mainly of fine, granular diopside with some wollastonite and minor calcite and feldspar. The skarn is oriented N50 E with a 70° NW dip. The skarn is in contact, to the east, with dolomitic marble; to the west, the skarn becomes a calc-silicate rock through a gradual increase in diopside and feldspar.

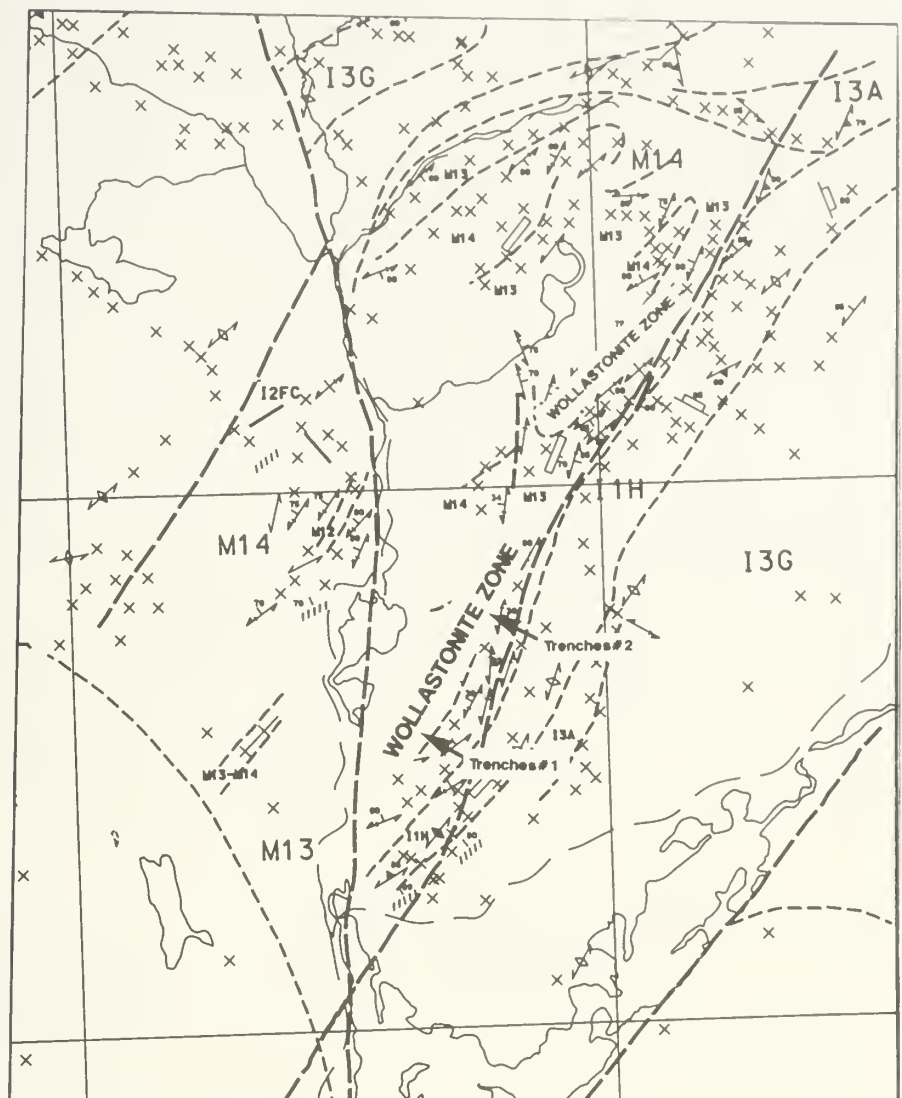


Figure 3. Lake aux Grandes Pointes zone (see legend Figure 4).

Four trenches were dug in the southern part of the wollastonite zone. Channel sampling in two of these trenches gave the following results:

	Trench # 1		Trench # 2	
	1st sample	2nd sample	1st sample	2nd sample
Quartz	0.2%	0.2%	0.2%	1.3%
Wollastonite	50.3%	63.4%	49.7%	34.3%
Diopside	30.4%	24.6%	34.0%	36.4%
Calcite	2.5%	0.8%	3.6%	7.6%
Microcline	7.9%	4.4%	7.6%	8.4%
Plagioclase	9.4%	7.4%	5.8%	12.2%

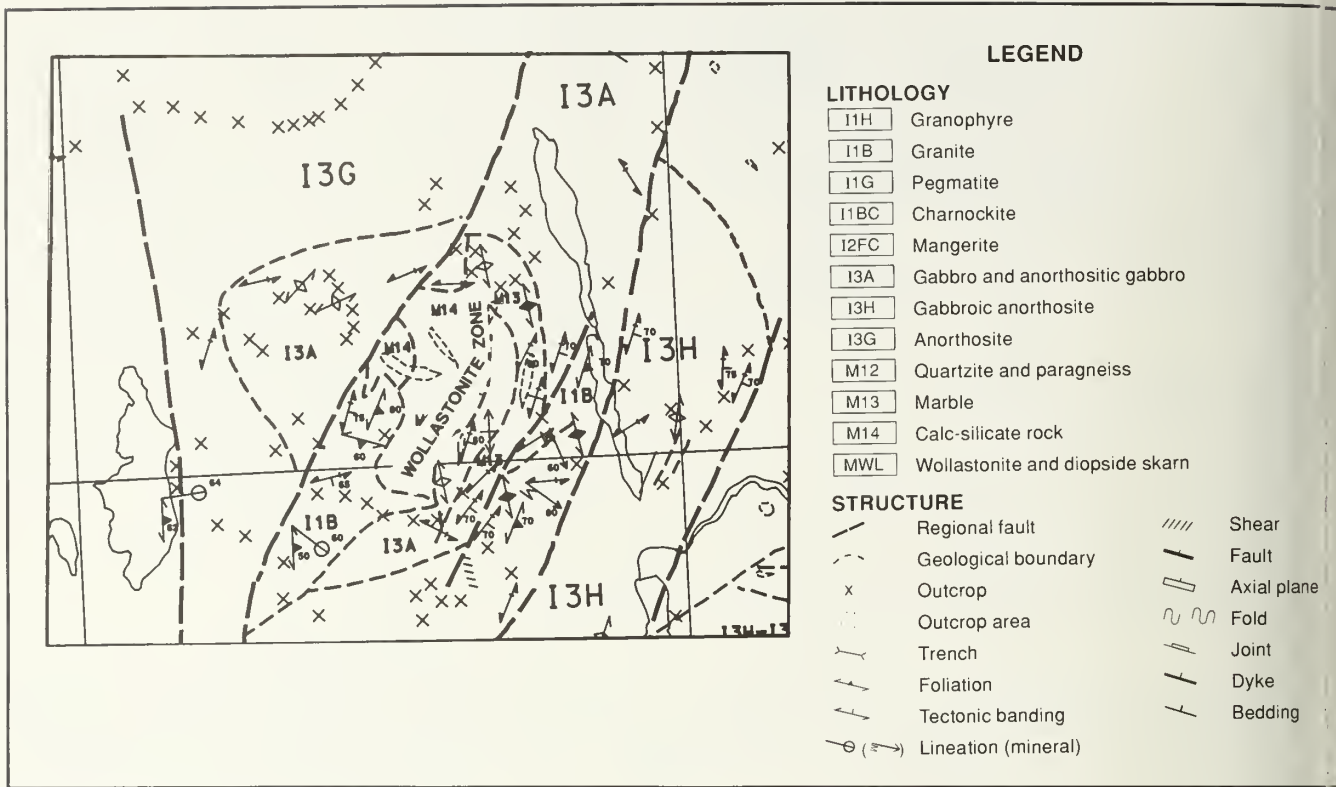


Figure 4. Little Peribonca River Zone

In the Little Peribonca River zone, showings of wollastonite rock, similar to the Lake aux Grandes Pointes skarn occur along a northeast-oriented zone (Figure 4). This zone is more than 1 km long. Grab samples contained up to 40 percent wollastonite (visual estimation). More detailed mapping and sampling are needed for a better evaluation of the zone.

### Montréal-Gatineau area

This area (Figure 5) is the host of more than 100 wollastonite occurrences (Simandl et al., 1990). Most of them are found in the central part of the area, in a large zone of migmatitic and granitic gneisses which have been intruded by anorthosite and related rocks of the Montréal anorthositic complex. A few occurrences are also found in the western part of the area in metasedimentary inclusions within the Wakefield syenitic batholith.

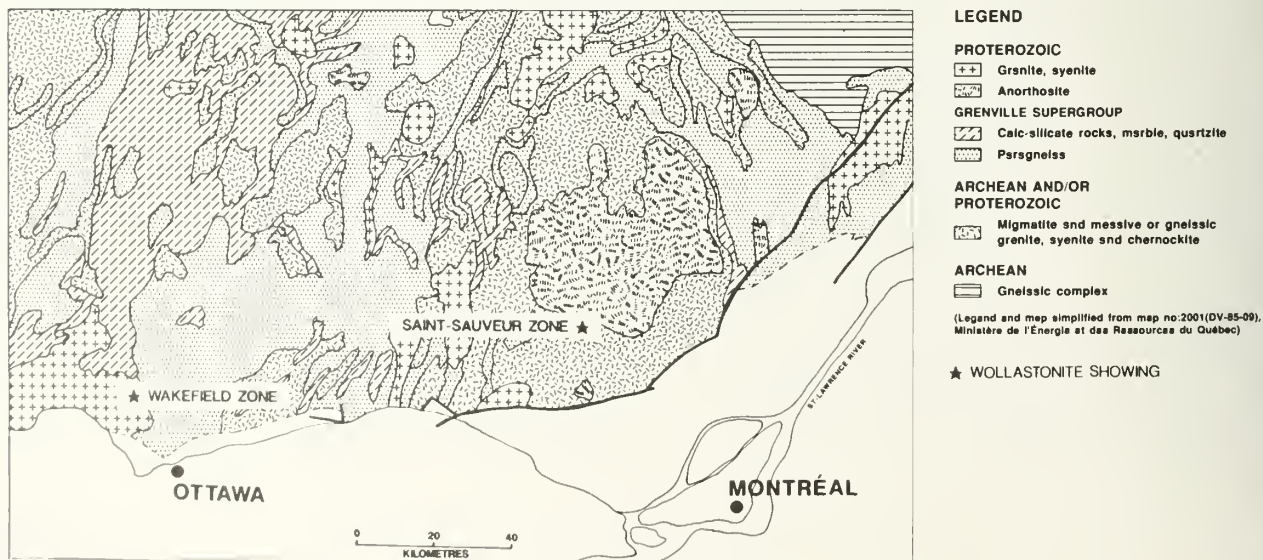
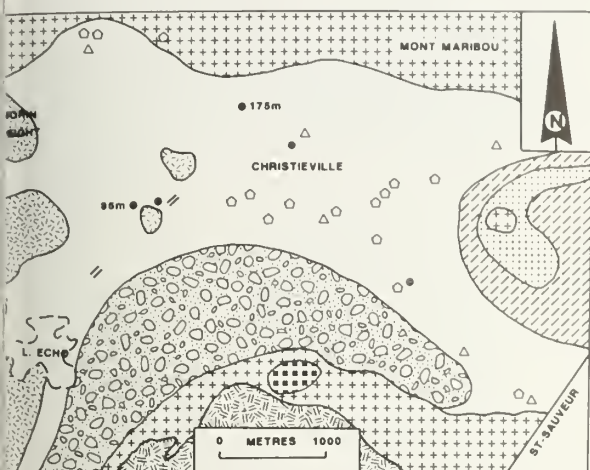


Figure 5. Montréal-Gatineau area.





**WOLLASTONITE OCCURRENCE:** ● MAJOR, ○ MINOR,  
△ ERRATIC BOULDER, • DRILL HOLE (CUTTINGS)

#### LITHOLOGY

OVERBURDEN	QUARTZITE
DIABASE	RUSTED BIOTITE AND GARNET QUARTZO-FELDSPATHIC GNEISS
ANORTHOSITE	SYENITIC ROCKS
TRANSITION ZONE (gabbro, norite, jotunite)	CHARNOCKITIC AND GRANITIC WITH AMPHIBOLITE ZONES
MARBLE	

(Adapted from Simandl et al., CIM Bulletin, Feb. 1990)

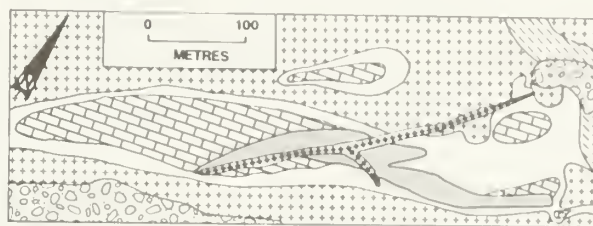
Figure 6. Saint—Sauveur zone.

Two zones of wollastonite occurrences will be described to illustrate some of the most favorable environments for exploration. The information given here is drawn from Simandl et al. (1990).

The Saint-Sauveur wollastonite zone (Figure 6) occurs in a zone of metasedimentary rocks which is located in the transition zone at the southern edge of the Morin anorthositic complex. Marbles, quartzites and quartzofeldspathic gneisses of the Grenville Supergroup are the main constituents of these metasediments.

About 30 wollastonite occurrences have been reported from the Saint-Sauveur zone. Most of them are associated with the marbles. Some contain disseminations of wollastonite in marble; in others, wollastonite rock forms regular or tabular zones up to 1m thick. A typical wollastonite rock is composed of wollastonite (30-60 percent), clinopyroxene (2-20 percent), calcite (5-60 percent) and feldspar (0-5 percent). Wollastonite is present in prisms 2-50cm long; the color of the rock is pale green to white.

The Wakefield zone (Figure 7) is located in the Manicouagan Plateau near Ottawa. It occurs in a large 600m x 200m inclusion of metasedimentary rocks within the Wakefield syenitic batholith. The inclusion consists of marble



#### LEGEND

OVERBURDEN	WAKEFIELD SYENITE
PYROXENITE	MARBLE
PEGMATITE	WOLLASTONITE
GNEISS	

(Adapted from Simandl et al., CIM Bulletin, Feb. 1990)

Figure 7. Wakefield zone.

and wollastonite rock, which are separated from syenite by a 1-5m thick pyroxenite zone. Wollastonite rock outcrops are scattered over a zone measuring 330m x 20m in the eastern part of the inclusion.

The wollastonite rock is white in colour where fresh and grey or tan where weathered. The rock is coarse grained (5-15mm) with a porphyroblastic-granoblastic texture. The main constituents are wollastonite (30-70 percent), calcite (25-65 percent), and clinopyroxene (<5 percent).

### North-Shore area

Wollastonite is also present in the North-Shore area where two significant showings were recently discovered, in course of geological mapping.

The first showing is situated along the coast near the locality of Rivière-Pentecôte. It was discovered during a study of the Rivière-Pentecôte anorthositic complex (Nantel and Martignole, 1991). It occurs in an outcrop (75m x 6m) of metasedimentary rocks within the contact zone of the complex (Figure 8). The metasedimentary rocks form distinct layers, 1 to 10m thick, in leuconorite. The layers are composed of wollastonite gneiss, wollastonite-diopside gneiss, and wollastonite marble. According to a visual estimation, the enclave contains about 40 percent wollastonite.

The second showing was found last year during reconnaissance geological mapping survey in the Manicouagan plateau area (Gobeil, 1991) (Figures 8 and 9). A wollastonite zone within aluminous and calcareous paragneiss is enclosed in a granulitic gabbro-norite of the Manicouagan metamorphic complex. A grab sample revealed 54 percent wollastonite. Other constituents are quartz (14 percent), diopside (15 percent), calcite (8 percent), feldspar (7 percent), and grossularite (2 percent). The thickness and extent of the zone are not known.



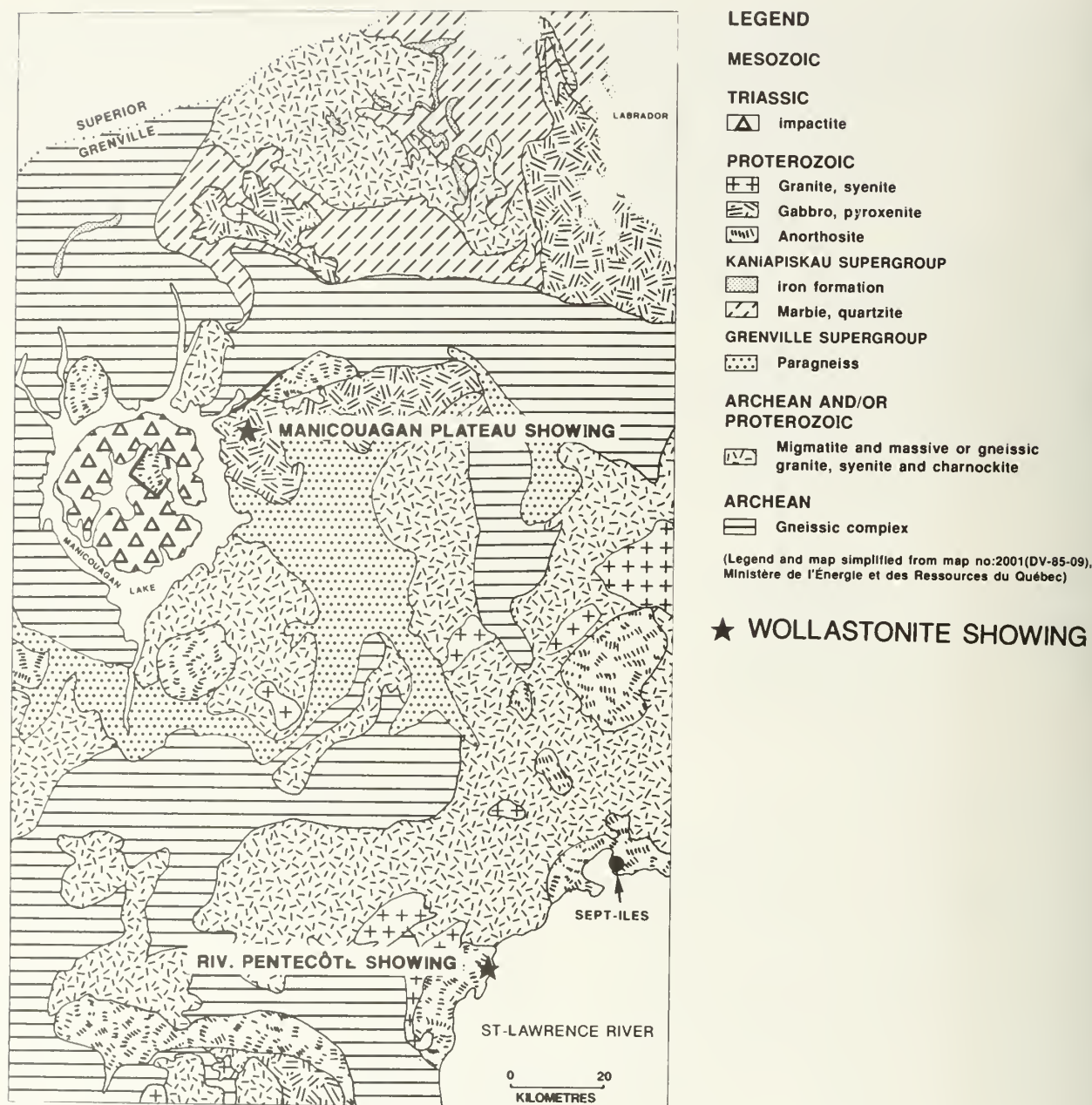


Figure 8. North Shore area.

## CONCLUSIONS

The potential for wollastonite within the Grenville Province in Québec appears evident. In addition, the Lake aux Grande Pointes zone shows the interesting possibility of recovering diopside as a by-product, which adds value to the treated ore.

In addition to their wollastonite potential, the zones of supracrustal rocks in the Grenville Province provide opportunities to discover other useful industrial minerals,

such as brucite, magnesite, olivine, calcitic and dolomitic marble, quartzite, kyanite, graphite, etc.

The Grenville Province of Québec covers a vast and relatively unexplored territory. It will provide challenging opportunities for exploration companies seeking to increase their reserves of industrial minerals or to diversify their natural resources production.

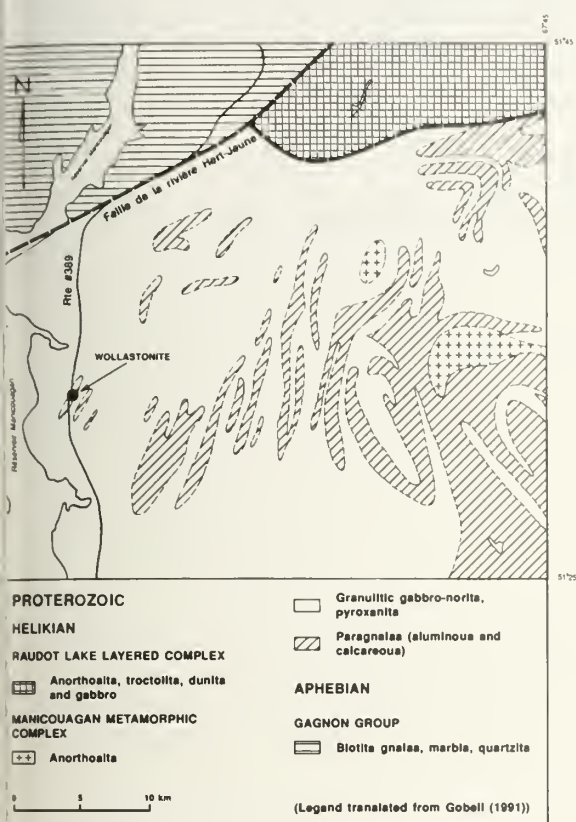


Figure 9. Simplified geological map of part of the Manicouagan Plateau.

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# Diamonds In Canada: An Overview Of Current Developments

By  
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## ABSTRACT

Exploration activity for diamonds in Canada has recently experienced a dramatic increase. Disclosure of a diamond discovery exhibiting features of a potentially economic deposit contained in a kimberlite pipe in the Lac de Gras area of Canada's Northwest Territories has sparked substantial interest in Canada and abroad and has triggered the largest staking rush in terms of area in the history of Canadian exploration.

In this paper, we report on the nature and extent of current exploration activity in Canada for diamonds (with special attention to Arctic regions), the results of this activity to date, and the context in terms of current world markets for diamonds.

## INTRODUCTION: CANADA'S DIAMOND POTENTIAL

As Levinson, Gurney and Kirkley (1993) show in Figure 1, a large area of northern and central Canada is underlain by a huge craton (part of the earth's crust and upper mantle that has attained stability and has been little deformed for a prolonged period of time), segments of which are very old, which forms the nucleus of the North American continent. Studies of the global distribution of kimberlites show that these rocks are mainly confined to ancient cratons such as the one found in Canada. In this context, the fact that Canada has the world's greatest expanse of cratonic rocks (Duke and Kjarsgaard, 1993) suggests that Canada has significant potential to become an economic producer of diamonds. Indeed, diamond indicator minerals (subcalcic high-chrome garnet, chrome spinel, high-magnesia ilmenite, and high-chrome chromite) and diamonds have been found in glacial deposits in numerous localities in Canada. These observations lead us to believe that, given sufficient time and funds for exploration, the chances of discovering diamonds in Canada in commercial quantities are good.

## DIAMOND EXPLORATION AND DIAMOND DISCOVERIES IN CANADA

As Bouchard and Cranstone (1993) report in their annual review of mineral exploration in Canada, the discovery of diamonds in kimberlite pipes and perhaps in lamproite intrusions in Canada clearly constitutes the Canadian exploration highlight of 1991 and 1992. (Figure 2 shows an idealized kimberlite pipe; after Levinson et al.) A number of gemstone quality diamond-bearing kimberlite pipes of possible economic grade were discovered in the Northwest Territories in addition to the as-yet uneconomic diamond-bearing kimberlites found in various Canadian localities since 1968.

There have been various previous indications that economic diamond deposits might exist in Canada. A few dozen diamonds have been found in glacial overburden deposits in the Great Lakes area of the United States. The materials from which the glacial overburden was formed may well have been carried south from Canada by continental glaciers. A diamond of about 33 carats, but broken and of little value as a gem, was reportedly found near Peterborough, Ontario prior to 1920. A second diamond

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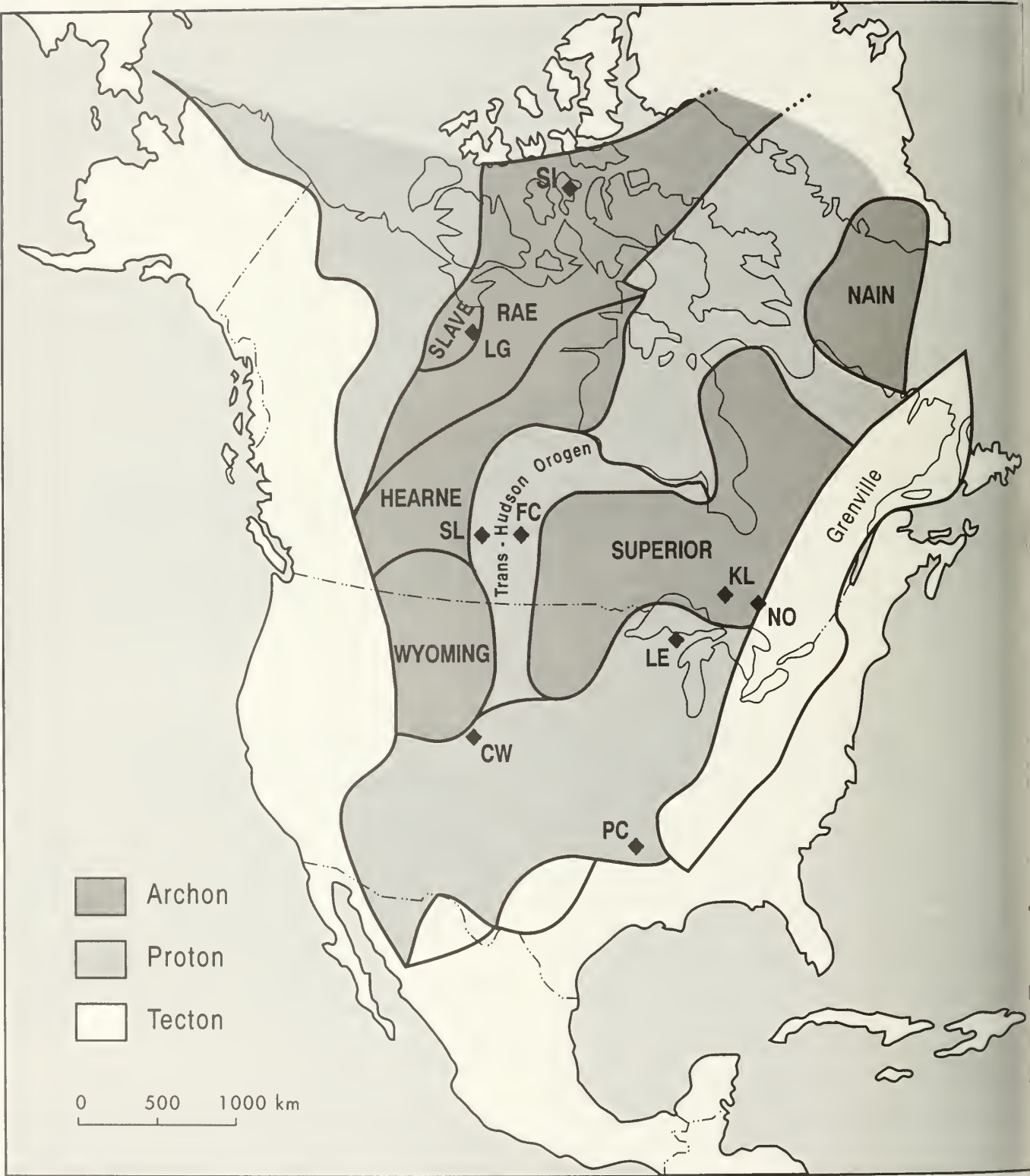
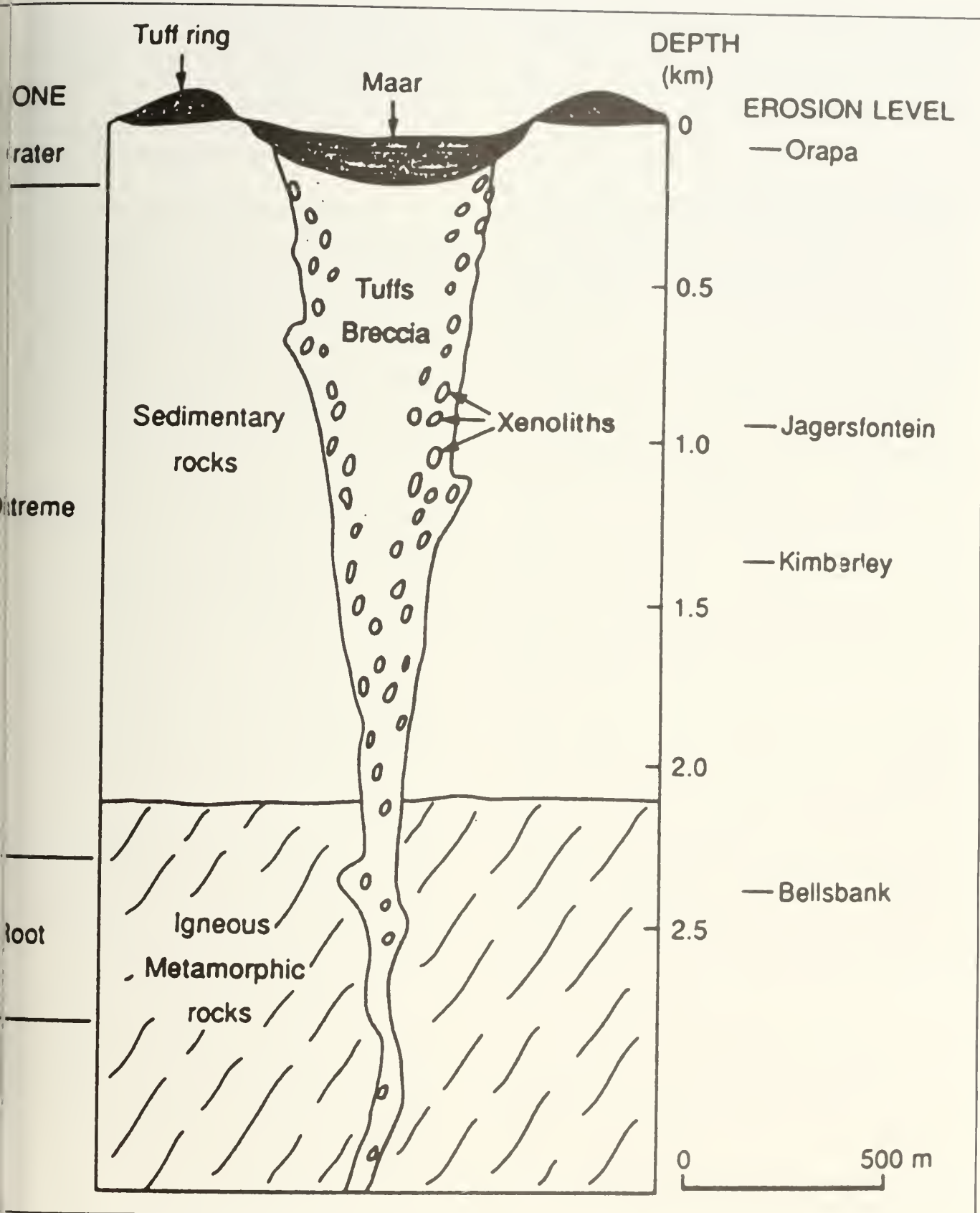


Figure 1. North America contains the world's largest Craton (Levinson, Gurney and Kirkley, 1992).



dealized model of a Kimberlite Pipe (Levinson, Gurney and Kirkley, 1991).



of about 0.255 carats in size was found in an esker near Timmins, Ontario, by Reno Jarvi. This diamond is of gemstone quality and was examined by scientists of the Royal Ontario Museum. The sources of these two diamonds have yet to be discovered.

Kimberlite intrusions containing micro-diamonds were found on Somerset Island, Northwest Territories in 1973-74; on Ile Bizard (near Montréal, Québec) in 1968; in Ontario near Kirkland Lake in 1983-84; and in one or two other Canadian localities, but did not yield diamonds of economic significance. Between 1988 and 1991, exploration turned up at least several dozen kimberlite pipes intruding post Precambrian Cretaceous and older rocks in Saskatchewan. At least 15 of these kimberlites were reported to contain diamonds, but most of them were micro-diamonds of no economic value. Several of the intrusions have yielded a total of 160 larger "macro-diamonds," most of them gem quality. However, these are apparently all very small diamonds. The average diamond content of all the Saskatchewan pipes reported on at time of writing is less than 10 carats per 100 tonnes and is too low to be economic.

Following the discovery of diamond-bearing kimberlite pipes in Saskatchewan, diamond exploration soon spread to Alberta and the Northwest Territories. A significant diamond discovery was made in 1991 by BHP Minerals and Dia Met Minerals at Point Lake, in the Lac de Gras area, Northwest Territories, about 200 km northeast of Yellowknife. A 145 metric tonne sample taken by drilling several large-diameter holes into one kimberlite pipe on the property yielded 101 carats of diamonds, one quarter of which appear to be of gem quality. A few of them are 1 to 3 carats in size. The surface area of the pipe, which is mostly covered by the water of Point lake, appears to be about 20 ha. Much larger bulk samples will have to be tested before it is known whether the deposit is minable. A stock exchange listing report filed by Dia Met Minerals stated that a kimberlite resource of 73 million tonnes grading 69 carats per 100 tonnes had been outlined to a depth of 220 m. In December, it was announced that core and surface samples of nine new kimberlite pipes indicated that all these pipes contain macro-diamonds. At least six of the new pipes are as large as, or larger than, the Point Lake kimberlite.

In November 1992, several micro-diamonds were also reported from kimberlite intrusions about 15 km southeast of Point Lake on a property owned by several other companies. Kimberlite intrusions are also reported on various other properties in the Point Lake area; however, at time of writing, there is no information concerning whether or not they contain diamonds.

The Point Lake discoveries have led to unprecedented staking in the Northwest Territories where some 7 million hectares (ha) had reportedly been staked, up from 2.2 million ha in 1991 and 356,000 ha in 1990. In Alberta, the December staking rush referred to earlier increased the area staked in 1992 to at least 26.1 million hectares, approximately 40 percent of the total area of the province.

A number of companies has been involved in diamond exploration activities in Canada particularly in the Northwest Territories, but also in Alberta and Saskatchewan as noted above as well as Manitoba, Ontario, and Québec. (Duke and Kjarsgaard report there are currently over fifty companies with land positions in the area of Lac de Gras alone.) The major international companies involved in exploration work have been De Beers Consolidated Ltd of South Africa through its Canadian subsidiary Monopros Ltd, Kennecott Canada Inc (the US arm of RTZ of Britain), and BHP Minerals of Australia in association with Dia Met Minerals Ltd. Companies such as Cominco, Teck, Cameco, Uranerz Exploration and Mining, Aber Resources Ltd, Southern Energy Resources Ltd, Ashton Mining, KWG Resources Ltd, and many others have also been involved.

## WORLD PRODUCTION

### Natural Diamonds

World production of natural rough diamonds in 1991, the latest year for which statistics are available, was estimated at close to 105M ct valued at some US\$5 billion or US\$50/ct. Out of this, 56M ct consisted of low value (50¢-\$5.00/ct) industrial diamonds, 35-40M ct of near-gem quality diamonds (\$5-\$50/ct), and 15-20M ct of gem-quality diamonds. In terms of value, gem diamonds represented between 75 and 80 percent of world production; near-gems accounted for close to 20 percent, and industrial diamonds 2 to 5 percent. World production of natural diamonds grew from 55M ct/y in 1983 to close to 105M ct/y in 1991. This growth, which can be accounted for mainly by Japan during the 80s, represents an increase of about 6M ct/y (Boucher 1993).

Natural diamonds are produced by some 20 countries; however, close to 95 percent of the world production by weight comes from only five countries, which are as follows: Australia (36Mct), Zaire (20Mct), Botswana (18Mct), Russia (15Mct) and South Africa (8.4Mct). In terms of value, Botswana, Russia, South Africa, and Zaire are in decreasing order the most important diamond-producing countries representing close to 75 percent of the world's production.

The quantity of diamonds in the ore (grade) varies widely from one mine to another but, generally, the grade falls between 0.3 and 1.3 ct/t. Grades as low as 0.05 ct/t and as high as 7.0 ct/t have been exploited. Gem and near-gem quality diamonds represent 30 percent by weight of the production in Ghana, 40 percent in Liberia, 50 percent in Australia, 70 percent in Botswana, 93 percent in Guinea, and 95 percent in Namibia.

### Synthetic Diamonds

Synthetic diamond competes with natural industrial diamond as an abrasive mineral, and mainly with silicon carbide (SiC) and alumina ( $\text{Al}_2\text{O}_3$ ), but also with cubic boron nitride (CBN) as manufactured abrasive materials. World production of synthetic diamonds in 1991 was estimated by the US Bureau of Mines at 360M ct. Synthetic diamonds have been produced commercially since the late 1950s after their invention in the U.S. by General Electric. In comparison with SiC and alumina, synthetic diamond production is not electricity-intensive.

In 1992, synthetic diamonds were produced in at least 16 countries. The most important producing countries are by decreasing order the U.S., the C.I.S., China, Ireland, South Africa, Japan, and Sweden. Smaller plants exist in Czechoslovakia, Yugoslavia, Romania, France, England, Korea, and Greece. New plants have been built in recent years in the U.S., England, and Korea. Leading producers are De Beers (South Africa), General Electric (U.S.), and Tomei (Japan).

Consumption of synthetic diamonds is reported to be growing at some 10 percent/year. Although it is an expensive product compared with SiC and  $\text{Al}_2\text{O}_3$ , synthetic diamond is more cost-effective because it cuts much faster and lasts much longer. In many applications, synthetic diamonds are preferred to natural industrial diamonds because they can be tailored to the customer's needs. Natural industrial quality diamond is used proportionately much less in industry today than was the case even 10 years ago, and applications are now confined to a fairly narrow and shrinking band constituting no more than 10 to 15 percent of total industrial diamond consumption (B. Cullingworth to B. Kjarsgaard, personal communication).

It is reported that Japan is at the forefront of conversion to superabrasives<sup>2</sup> as 60 percent of all abrasives products used in Japan have diamond components. Currently, 40 percent of abrasives used in Europe and 20 percent in North America are superabrasives. In Canada,

the gradual conversion from traditional abrasives (SiC and  $\text{Al}_2\text{O}_3$ ) to newer and better performing superabrasives is slowly eroding our markets. As a producer of traditional abrasives, Canada is negatively affected by the trend. Although Canada is an important consumer of synthetic diamonds, it is still not a producer.

### CANADIAN TRADE AND CONSUMPTION

Canada's imports of gem-quality diamonds and industrial diamonds were valued at \$211M in 1990 and \$189M in 1991; some 90 percent of the imports are estimated to be gem-quality diamonds. Imports of synthetic diamond dust or powder were 5.92M ct valued at \$4.64M in 1990 and 7.36M ct valued at \$4.45M in 1991.

#### Diamond Cutting (Manufacturing)

Natural diamonds are cut in some 30 countries. The major diamond cutting centres in the world are Antwerp, Belgium; Tel Aviv, Israel; New York City, U.S.A.; and Bombay, India. With the exception of India, which is a very small producer of diamonds, none of these countries mines diamonds. Other countries with important cutting centres include South Africa and the C.I.S. Newcomers are Australia, Thailand, China, Botswana, Sri Lanka, Indonesia, and Malaysia. It was recently reported that a new venture has been formed between Japan and Yakutia, a republic within the Russian Federation, to start cutting diamonds in Yakutia.

Diamond cutting is labour-intensive and, unless a factory is highly automated, it is not capital-intensive. Because of high labour costs, factories in the U.S. usually cut bigger and better quality diamonds. Belgium and Israel are in the middle of the labor-cost spectrum and, as such, they are generally involved in cutting stones of intermediate size and quality. India with its low labor costs cuts the smallest and least expensive diamonds. Employment varies widely from factory to factory, i.e. from 1 to 1,000 workers. It also varies widely from country to country, i.e. fewer than 500 cutters in the U.S. and close to 10,000 in the C.I.S. to hundreds of thousands in India.

The major steps in diamond cutting are: sawing (to remove flawed areas of the stone) with a saw and diamond dust or with a laser, or cleaving; rounding, which is also called "bruting", "shaping" or "girdling" (to round the corners); faceting; brilliantteering; and polishing.

<sup>2</sup>includes mainly synthetic diamonds, but also cubic boron nitride (CBN), and polycrystalline synthetic diamond shapes (PDS) and compacts (PDC).



## VALUATION AND SALES PROCEDURES

### Rough Diamonds

Between 80 and 85 percent of the rough diamonds produced in the world are marketed by De Beers through that company's Central Selling Organization (CSO). The valuation of rough mined diamonds is very complex and, according to the industry, diamonds are classified into some 5000 categories. Roughs are first sieved and sized. The stones are then separated into gems and near-gems. Gems are classified according to their *shape* (sawables, which can be sawn with a diamond saw, and makeables, which must be cleaved by hand), *clarity* (five categories), and *colour* (five grades, which are divided into sub-categories). Gems usually have a yield (weigh of cut and polished stone/weigh of rough) of 40-50 percent.

Near-gems are roughs with substantial impurities and other defects, which have a low yield, usually of only 15-25 percent and, depending on market conditions and labour costs, may or may not be cut and polished to produce a finished gem. Near-gems are divided into three basic categories: rejection #1, rejection #2, and rejection #3, each category being sub-divided into more categories on the basis of cleavage, which are chips (small and larger sizes) and cubes. These are clean areas of a stone that can be sawn or cleaved off and polished into a gem. After classifying the gems and near-gems, coated "frosted" stones are classified. Often the value of these stones can only be guessed because it is impossible to see inside the stone to determine its quality.

The CSO has been very successful in maintaining balance between the supply and demand of rough diamonds for some 50 years; it buys surplus production of rough diamonds from mines and stockpiles in periods of weak demand in the jewellery market and sells off its stockpiled roughs as demand picks up. De Beers can also apply production quotas to major producers when sales fall.

Rough diamonds are released to the market in a controlled way (to maintain balance between the supply and demand of different quality diamonds) by the CSO at "sights," which are held about every 5 weeks in Europe and involve about 200 carefully chosen buyers known as "sightholders." The majority of the sightholders are manufacturers who cut and polish the stones in their factories, although some wholesale firms that deal in rough diamonds also attend the sights. Once the stones are cut and polished, they are sold to diamond merchants, or wholesalers. Finally, the diamonds are sold to retailers and to jewellers.

### Cut and Polished Diamonds

To determine the value of a diamond, an appraiser looks at a combination of all the four "C's": cut, colour, clarity and carat (weight).

#### Cut

The cut of a diamond is the most important. The quality of a diamond is not determined by its shape (round, pear shape, heart shape etc.), nor by the number of facets. Rather, it is determined by the relative proportions of the table size, crown height, and the pavilion depth of the diamond, which determine brilliancy i.e. the amount of light reflected through the stone and by the angles of the facets, which determine the dispersion of light, which creates the fiery rainbow colours.

#### Colour

The rarest and best colour in diamonds is no colour at all. The colour grade is a measure of the amount of colour present in a diamond. Most diamonds have a tinge of some colour (most often yellow or brown).

#### Clarity

This is a measure of the number of flaws (inclusion and imperfections). Inclusions are crystals of other minerals; imperfections are feathers, blemishes, cracks, etc.

#### Carat

One carat is equivalent to 0.2 gram. A carat is normally divided into 100 points. Because larger diamonds are rare, a 1 carat diamond will cost more than a cluster of 20 diamonds weighing a total of 1 carat.

### Uses

Gem-quality diamonds are used mainly in jewellery. Credit Lyonnais Laing of Credit Lyonnais Securities reports that the three major markets for diamond jewellery are the U.S. (30 percent), Japan (30 percent), and Europe (17 percent). Since a considerable proportion of the rough stones is lost during cutting and polishing, only about 15 percent by weight of the rough stones mined end up in jewellery.

Diamonds, both natural and synthetic, are the hardest substance known to man, so they are used in equipment that drills, cuts, grinds, and polishes rocks and other materials such as granite and marble, non-ferrous metals, carbon fibre, composites, nonmetallic materials such as glass, refractories, ceramics, concrete, plastics, masonry bricks, etc. Natural and man-made diamonds are widely used in the automotive, high-technology, and aerospace industries. Synthetic diamonds have certain advantages from an environmental perspective over conventional abrasive products, especially aluminum oxide.



## Prices

In 1991, published average mine prices of roughs including gem, near-gem and industrial diamonds varied widely by country from US\$6/ct in Australia, US\$27 in Zaire, US\$67 in Botswana, US\$95 in Russia, US\$105 in South Africa, US\$157 in Angola, US\$208 in Sierra Leone, US\$300 in Guinea, and US\$315 in Namibia. South Africa mines produced roughs that varied in price from US\$60 to US\$300/ct. It is reported that the prices of rough diamonds have increased about 1 800 percent during the past 40 years, which means that a rough diamond that sold for US\$100 in 1949 would sell for about US\$1 800 in 1991. In comparison, a consumer item costing US\$100 in 1949 would sell for about US \$590 in 1991.

In 1991, prices of U.S. cut diamonds, by size and quality varied widely from about U.S.\$900/ct to more than U.S.\$7000/ct. It is estimated that, taking into account losses during cutting and polishing as well as commissions paid to intermediaries between the mine and the jeweller, the retail price of a diamond in jewellery is 5-6 times the price of the rough stone at the mine.

Natural industrial diamond grit (40 microns to 100 microns) and powder (-40 microns), synthetic grit and powder, and industrial stones imported into the U.S. in 1991 were valued at US\$0.63/ct, US\$0.74/ct, and US\$6.94/ct respectively. There are hundreds of types of synthetic diamonds and synthetic diamonds can be coated with metals such as copper or nickel for specific applications. The prices of synthetic diamonds vary widely from 20¢/ct for friable material with irregular shape, to \$1-\$2/ct for polishing material, to several dollars per carat for blocky, regular shapes with excellent crystal structure.

## Outlook and Production Forecast

Currently, there is a surplus of natural diamonds in the marketplace, a situation which is likely to last another two or three years. However, industry sources predict that, by the mid- to late-90s, consumption of diamonds should increase

as western economies recover and as sales in southeastern Asian countries increase due to their rapidly growing economies. After the year 2000, sales to eastern Europe are expected to pick up. Johnson, Marriott and von Saldern (1989) estimate that, by the year 2000, world production of natural diamonds will vary from 84M to 136M ct/y, with a best estimate of 113M ct/y.

## ACKNOWLEDGEMENTS

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# Canada's Zero Effluent Potash Mine

by  
Brian V. Roulston<sup>1</sup>

## ABSTRACT

Potash is Canada's leading industrial mineral in terms of value of production, with 11.1 M tonnes of muriate of potash produced in 1992 for a value in excess of \$1 billion U.S. Each tonne of potash produced generates about 2 tonnes of waste salt, together with slimes and brine. The disposal of these waste products, particularly the salt and slimes which are discharged on the surface, has recently become an environmental concern. This concern is forcing companies and regulatory authorities to review disposal practices.

In New Brunswick, on Canada's east coast, Potash Company of America operates a mine at which 2 M tonnes of potash ore and 0.5 M tonnes of rock salt are mined each year. The mine is situated in an environmentally sensitive area, noted for its dairy farming and salmon angling. In such an area it was recognized that the storage of waste on surface would be unacceptable, and the mine was designed around this principle.

Three main waste streams – salt, slimes, and brine – must be managed as an integral part of the mining system. Around 1.5 M tonnes of fine salt tailings from the milling process and the rock salt screening operation, are sent directly to the active cut-and-fill potash stopes to be used as backfill. Slimes and excess brine from the mill are piped underground as a slurry to be discharged into one of the basin shaped stopes created by mining of the rock salt. While the slimes settle out, the clarified brine is withdrawn from part of the stope to be pumped to surface as a feedstock for the evaporator – a process which recovers the contained potash values in the brine.

By designing a system which integrates the mining, processing and disposal of all product streams, and by careful production planning, it has been shown that zero effluent potash mining is possible and points the way for the industry in the future.

## INTRODUCTION

Potash is Canada's leading industrial mineral with 11.1 million tonnes of potassium chloride (approximately 11.1 million tonnes  $K_2O$  equivalent) produced in 1992 for a value of over \$1 billion U.S.

Production started in Saskatchewan in 1958 and within a decade ten mines were in operation (Figure 1), extracting potash ore from the Devonian Prairie Evaporite formation. In 1983, production began in New Brunswick, with two operations now mining the evaporates of the Carboniferous Windsor Group and generating about 15 percent of Canada's total production in 1992.

Almost 50 percent of the world's reserves of potash are in Canada. Although reserve figures vary widely (Muesy, 1984) it has been estimated that in excess of 300 billion tonnes of ore is recoverable in Saskatchewan by conventional and solution mining methods, sufficient to maintain present production levels for over 5000 years.

New Brunswick's reserves are reported by Webb and Barnett (1986) to be on the order of 700 million tonnes in situ, of which 350 million tonnes have been conservatively estimated by Mayhofer (1984) to be mineable.

The ore in both regions is mineralogically simple, averaging in the order of 40 percent KCl (25 percent  $K_2O$ ) and 60 percent NaCl, with an insoluble fraction ranging from 0.5 - 5.0 percent composed mostly of clay minerals (chlorite, illite), anhydrite, dolomite, hematite and quartz (Mossman et al., 1982). With run of mine ore grade typically in the range of 20-25 percent  $K_2O$ , recovery around 85-90 percent and a product grade of 60-62 percent  $K_2O$ , 3 tonnes of ore are mined for every ton of muriate of potash produced. Thus, in Canada, almost 25 M tonnes of waste salt together with slimes (the insoluble fraction of the ore and fine salt) and large volumes of excess brine must be disposed of each year. These wastes are dealt with quite differently by the mines in Saskatchewan and in New Brunswick.

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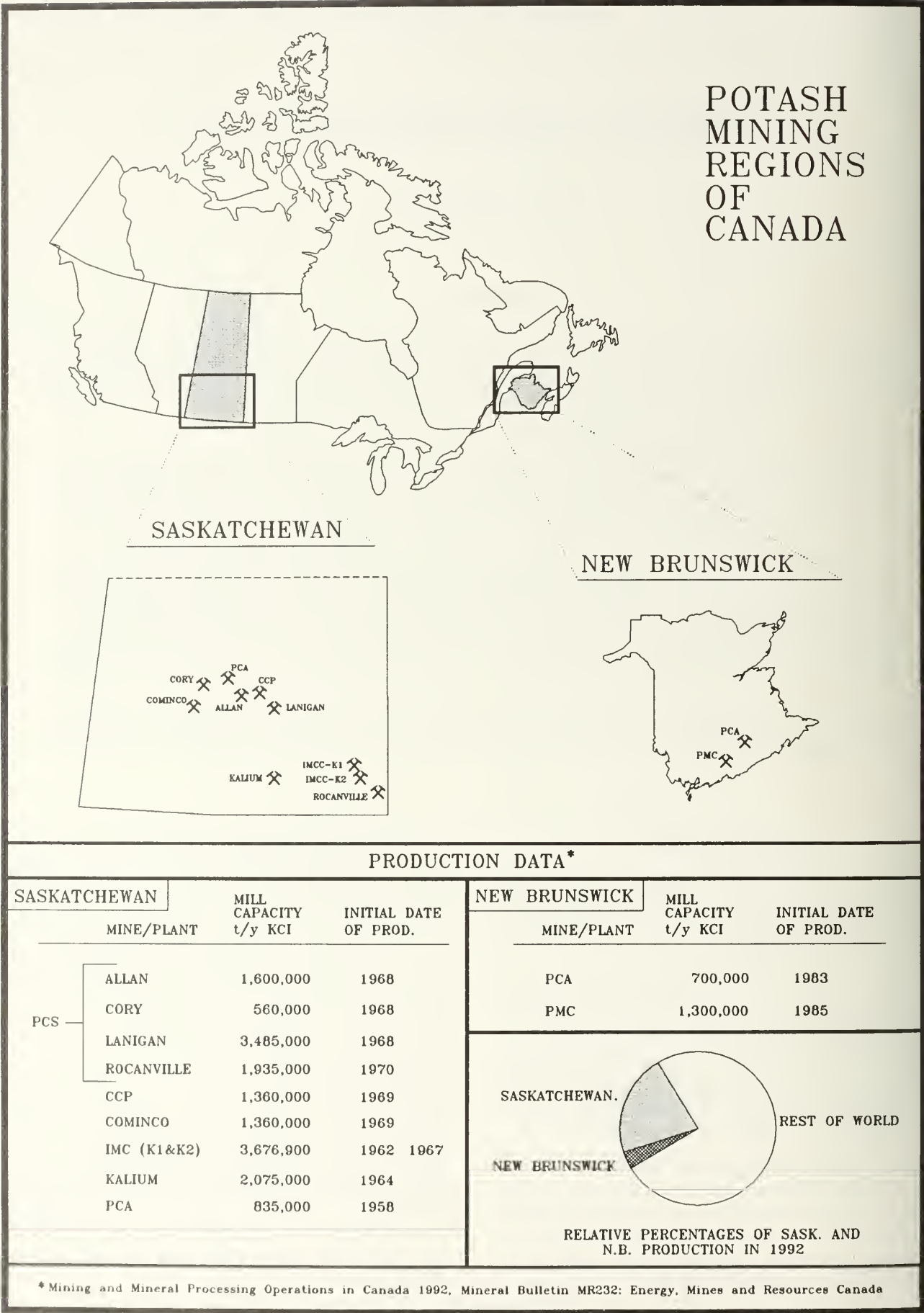


Figure 1. Potash mining regions of Canada.

## WASTE MANAGEMENT

### Regulations

While the majority of laws governing mining in Canada are within provincial jurisdiction, the regulation of environmental matters is shared by both the federal and provincial governments. Although the areas of regulatory responsibility often overlap, it is the provinces that have taken a leadership role, within their jurisdiction, in determining policy for the management of waste produced by the potash industry. In Saskatchewan, the Department of Environment and Public Safety in 1988 established a guideline that industry should work toward net zero discharge of waste by the year 2000. Such policies were introduced due to concern over potash mines' waste disposal practices (Potash and Phosphate, 1992). Most visibly this waste is in the form of increasing large waste salt tailings piles which, it has been estimated by Hart (1985), would cover 1600 km<sup>2</sup> of land in Saskatchewan by the time that the resource is depleted, if present disposal practices continue. Concerns have also focused on the long term environmental impact that brine run-off from these piles may have on the ground water resources. In Europe, for example, with its longer established potash mining industry, the practice of surface disposal of waste salt has led in some instances to extensive ground water salinization which is progressing outwards from the source at a rate of up to 100 m/year (Prugger, 1992).

In New Brunswick, waste management practices must meet criteria established through rigorous environmental impact assessments which are tailored to site specific environmental requirements. No permanent waste storage is permitted at either of the two operations.

Despite unresolved questions as to duplication of process by various agencies and jurisdictions, an initiative under the new Canadian Environmental Assessment Act proposes that the federal Environmental Assessment Act will be triggered by projects included in a defined Comprehensive Study List. Potash mines with an annual capacity greater than 1.5 M tonnes/year are now included on this list due to the public's concern over waste disposal practices, and automatically require a federal EIA. Such projects, as well as smaller capacity operations, could also be screened into a provincial EIA process by the local regulatory authorities.

### Potash Mine Waste

In Canada, as elsewhere, the problem of dealing with the brine producing waste salt piles is twofold. As a first step, the annual addition of 25 M tonnes of fresh tailings to the existing piles must be slowed down and eventually stopped. De Souza (1992), Prugger (1992) and others

have suggested ways in which the production of tailings can be reduced, and how backfilling with tailings might be incorporated into the mining cycle. According to De Souza (op. cit.) the increased costs of underground disposal could be offset by the geotechnical benefits, including improved ground control, reduced risk of mine flooding and the potential for greater extraction. However, there are also major logistical challenges to be overcome as production is typically from a relatively thin, highly stressed ore body in which the mining panels are over 10 km from the shafts.

The second part of the disposal problem concerns existing waste salt piles. These presently total over 250 M tonnes, covering 35 km<sup>2</sup>. To help provide a scientific basis for any discussion regarding the fate of these piles and to aid in rational decision making, Hart (1985) and Haug and Reid (1991) have examined decommissioning options ranging from surface disposal with perpetual maintenance, to underground disposal by brine injection into deep saline formations and backfilling of mine workings. Also, Fredlund and Mittal (1989) have examined the history of work on salt tailings and addressed areas of research which are considered necessary to provide a better understanding of the long term geotechnical properties of the tailings. Research into long term deformation and slope stability has now been carried out in laboratory studies (Fredlund, 1991) and in the field by instrumenting actual tailings piles (Pufahl and Fredlund, 1991), adding to the work of Pufahl (1983). The role of climate change and the effect of long term weathering processes in the development of cavities and solution structures has now been reported by Landine and others (1992) and other workers.

Recognizing that brine can alter the geotechnical properties of soils, Barbour and Yang (1991) have synthesized the information available in this area to help provide a better understanding of the effect of brine contamination on clay barriers. Problems of brine seepage have been documented by Kent and others (1983), Tullin and Pufahl (1983) and others, leading to a more detailed examination of the stratigraphy and physical properties of the soils in the vicinity of tailings piles together with the construction of additional monitoring wells and the modification of collection ditches. In one instance, (Reid and Maki, 1991) when brine seepage had the potential of contaminating an aquifer and thereby affecting a municipal water supply, the actual tailings disposal practice has been modified. By cycloning the tailings, it has been possible to partially copy the European practice of dry stacking. This approach allows a reduction in the aerial extent of the waste salt pile through an increase in height and, more importantly, leads to a smaller volume of brine having to be contained and managed.

Run-off brine from discharge of the slurried tailings and slimes, and that generated from dissolution of the waste salt by precipitation, once contained and collected, is typically disposed of in Saskatchewan by pumping to an injection well which discharges into one of the widespread permeable formations which underlie the mining level. An alternate brine disposal method is used by one New Brunswick mine which discharges its brine through a 34 km long pipeline into the Bay of Fundy.

## ZERO DISCHARGE MINING

### Setting

In 1983, after 10 years of exploration and development, production began from the first potash mine in New Brunswick. Recognizing that surface disposal of mine wastes would be environmentally unacceptable in an area of rolling hills, dairy farms and salmon streams, and with a maritime climate, the mine was designed to integrate the waste streams into the mining cycle.

Figure 2 shows schematically the wastes streams that are produced as part of the milling process and how they are integrated with both potash and salt production.

### Slimes

In the mill, once the potash ore has been crushed, saturated brine is added to form a slurry from which clays are removed by a multiple cyclone unit. This centrifugal effluent, together with the fine salt and potash which cannot be removed in the later flotation steps of the milling process, is sent to a thickener. The slimes underflow from this thickener, with a bulk density of 50 percent, is then pumped to the mine for disposal in empty salt stopes.

A schematic cross section through the evaporation structure (Figure 3) shows how the salt stopes are developed as ponds for slimes disposal. The stopes are typically on the order of 300 m long, 20 m high and 20 m wide and are usually configured in a connected series. This allows slimes discharge in one stope, with settlement of the fine solids as the clear saturated brine is recovered from the connected adjoining stope.

### Brine

The clean brine from the slimes together with brine drained from salt tailings in the potash stopes is saturated in potassium and sodium chloride and pumped back to surface. This reclaimed brine from underground is added

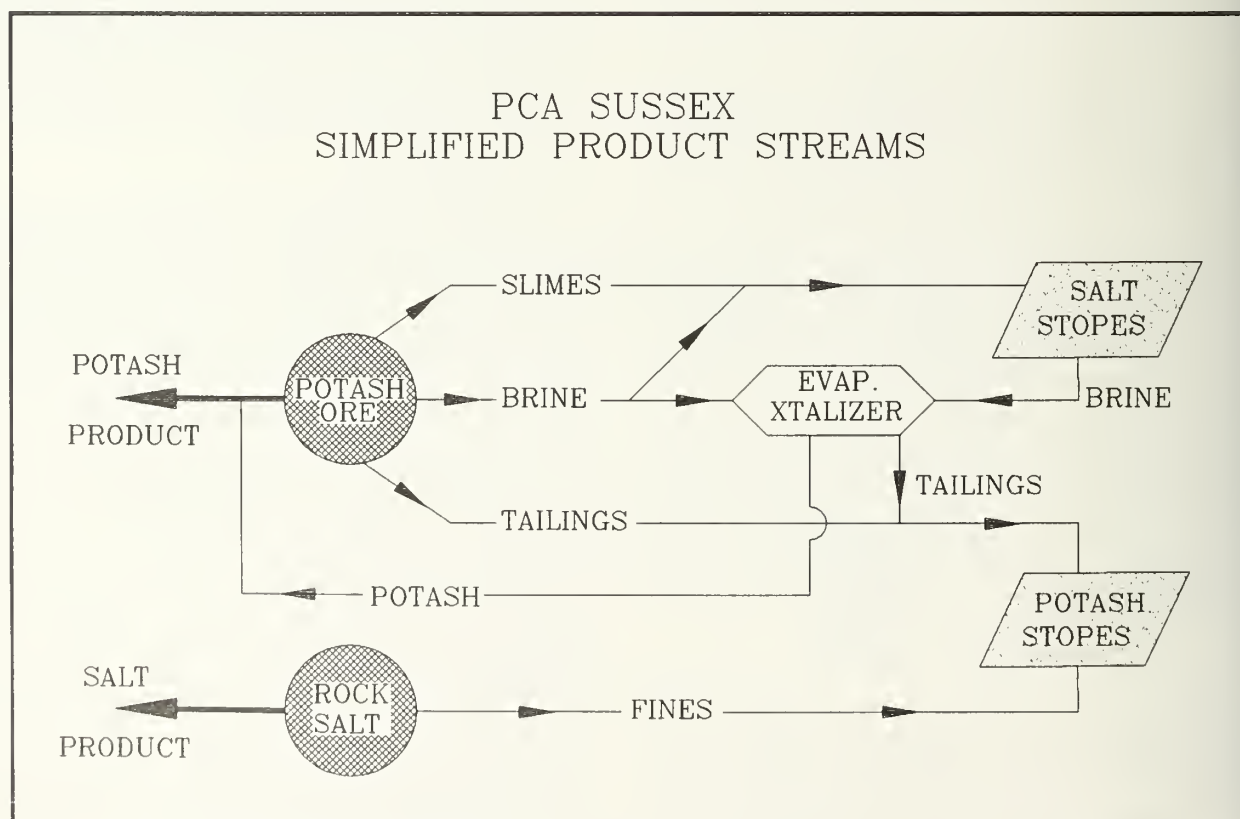


Figure 2. PCA Sussex simplified product streams.



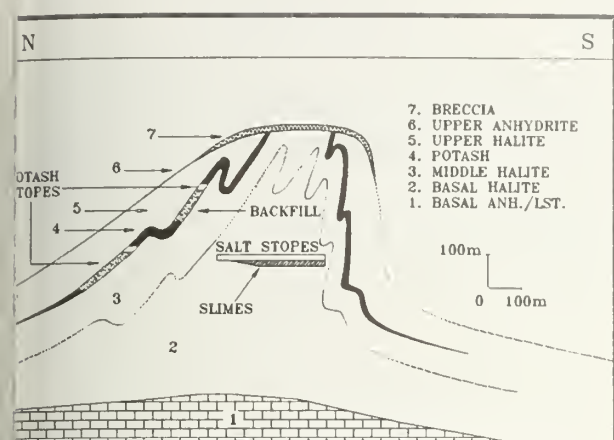


Figure 3. Schematic section through PCA evaporite structure.

plant brine generated from dust collected by electrostatic precipitators and from potash leaching which is necessary to maintain product grade. The brine stream is heated, then sent to one of three crystallizers in which potash crystals are grown by evaporative cooling. This is added to the potash product stream, helping to augment the mill's recovery. The spent brine with its high salt values is sent to an evaporator, and under partial vacuum, the salt is removed. As the salt does not meet product specifications, it becomes part of the tailings stream for direct disposal underground. The condensate produced by the evaporator is recirculated into the mill process to be reused as leach water.

In summary, the excess mill brine is used to transport slimes underground for disposal in the basin shaped salt stopes. As the slimes settle out, clear brine is reclaimed and pumped back to surface as feed stock for the crystallizers and evaporator. This generates potash for product, salt for underground disposal and condensate for further brine production.

The closed multi-loop brine system shows part of the close relationship between the mining method and the milling process, and demonstrates how liquid wastes can be contained and managed without surface disposal. With potash crystallization, the brine, which would normally be regarded as a waste with its associated disposal costs and potential environmental liabilities, becomes a valuable part of the mill feed stock. This helps to improve recoveries and optimizes utilization of the resource.

## Tailings

In the section on slimes, it was described how the slays are removed from the crushed ore as a first step in the milling process. The potash crystals are then recovered by a series of flotation steps which includes secondary crushing and screening of rougher tailings to maximize recovery. Rather than following the practice of other

mines and discharging the underflow of salt tailings for surface disposal, they are sent to a bank of conveyor centrifuges to be debrined. The recovered brine is reused in the milling process, while the salt tailings, which now have a moisture content of between 6 and 8 percent, are conveyed directly to one of two 200 mm drop pipes in the service shaft. No surface storage or disposal is used.

Underground, on the working level at -580 m, the tailings are reclaimed from a surge bin and conveyed to one of the active stopes, where they are spread out by scooptram to form the floor for the next cut. The placement of tailings as backfill represents the single most important aspect of the mine's ability to dispose of its waste salt stream and is an integral part of the mining cycle. For those interested in the geotechnical aspects of salt tailings as backfill in this application, they are referred to Beddoes et al. (1989).

Potash stopes, developed both above and below the main working level are in the order of 800 m long with a vertical height of 120 m. This block of ore is defined by the development of 20 percent tailings ramps at either end, connecting a basal sill cut. The block is split by a central ramp used to convey ore from the stope (Figure 4).

A mining cycle begins with the tracked road header style mining machine cutting out one half of the stope from the central ore ramp. With the variability of ore body width, both on strike and dip, this operation may take from 1 to 4 months, depending on the volume of ore in that particular cut. If the ore being mined is greater than 40 m wide, stubs are developed and these are converted to pillars, if required, in progressively higher cuts in the ore body.

While mining is progressing in one half of the stope (Figure 4), the other half, which has just been mined through, is filled with salt tailing to within 2.4 m of the back. This serves as a new floor for the mining machine on its next cycle and allows a further 4.3 m to be cut from

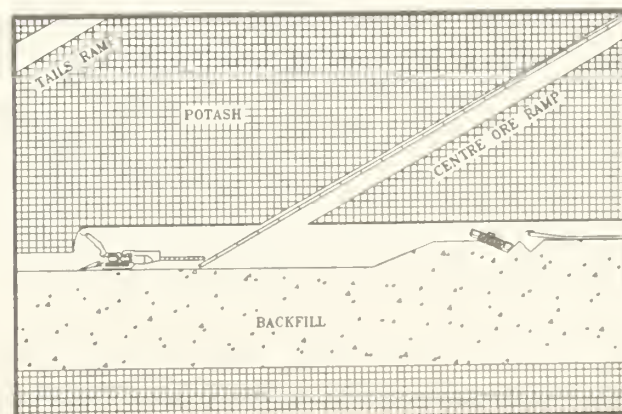


Figure 4. Longitudinal section showing PCA mining method.

hanging wall to footwall for the length of the stope. This mechanized cut-and-fill method of potash mining results in extremely efficient resource exploitation. Except for cases when the ore is unusually wide or has a flat dip and localized pillars are required, 100 percent of the ore in each stope is mined with only a single 12 m pillar left between the upper and lower series of stopes.

While the waste salt backfill offers hanging wall support in steeply dipping sections of the ore body, in areas of low dip angle effective backfilling can be troublesome because of the incompatibility of the large scoop-trams which spread the fill and the wedge shaped cavities which remain after cutting the hanging wall. Also, with settlement of the fill, large continuous gaps develop along the hangwalls of such stopes. In these areas, the hanging wall must be overcut for ground control purposes, resulting in ore grade dilution. Where this situation exists, the tailings are slurried with recirculated brine, in a portable in-line mixing tank positioned outside the stope. This slurry is then piped using gravity into the gap between the hanging wall and the fill, to provide the necessary widespread passive support to the shallow dipping hanging wall.

The effectiveness of slurried fill in such situations has led to large scale testing in which the complete tailing stream (200-250 t/h) has been reslurried underground and discharged into one half of a complete stope (50,000 dry tonnes of fill/lift). While the geotechnical and logistical aspects of this work are still being studied, it appears that slurried tailings may have certain advantages over mechanical placement of dry fill in particular applications.

### Salt Mining

As discussed earlier, rock salt is produced as a product by mining the high grade halite in the core of the evaporite structure in such a way that slimes can be disposed of in the empty salt stopes. Crushing and screening of the raw salt generates fine salt which does not meet product sizing specifications and so is regarded as a waste. This is added to the underground tailings disposal system and conveyed to the potash stopes to be used as backfill along with mill process tailings.

While the underground disposal of fines from salt mining is not unique, in this case, by integrating this waste into the mill tailings disposal system it performs a useful function as part of the backfill which is required in the cut-and-fill potash stopes. Approximately 10 percent of the backfill originates as rock salt fines.

### CONCLUSIONS

By developing a plan which integrates the waste disposal streams with the mining cycle, PCA has demonstrated that it is possible to operate a potash mine without surface waste disposal and with zero effluent discharge into the environment. While the costs of operating such a mine are higher than those for a "conventional" mine, as indicated by a 1989 tailing survey of Canadian mines (Amaratunga, L.M., pers. comm. 1992) showing the average backfill costs are eight times that of surface disposal, this is partially offset in the longer term by a number of positive factors.

- Mining with backfill allows extremely high extraction and therefore greater utilization of the resource as the waste salt backfill performs the ground control function of traditional pillars.
- Closure is controlled by the fill which has the effect of maximizing safety to workers and equipment.
- The backfill reduces the development of regional stresses, which evolve as large areas of contiguous stopes are mined. This support precludes the propagation of cracks through the hanging wall to overlying waterbearing clastic sediments, which is a concern of a potash operations.
- By minimizing closure in the stopes, surface subsidence can be controlled. Over potash deposits of approximate the same depth as the Sussex mine, but mined without backfill support, such subsidence can represent over 75 percent of the mining height after a few years (Whittaker and Reddish, 1989).
- Eventual mine closure and reclamation costs can be calculated and planned for which is not the case at operations with salt tailings piles and slimes ponds. These wastes represent an environmental threat (Potash and Phosphate, 1992) and their fate is still open to public debate.

Despite the logistical challenges and the additional operating costs involved in the elimination of surface waste disposal practices, there is an attempt by the potash mining industry in Canada to move towards this goal. While all of the features which PCA has been able to integrate into its zero discharge mining system may not be applicable to other mines, with their unique operating conditions, it does indicate that the adoption of various technologies and the incorporation of non-traditional mining methods can be of use in reducing or eliminating wastes. It is becoming recognized that the avoidance of potential environmental impact is preferable to compensation for future losses and that the best way to achieve such avoidance is by pollution prevention rather than pollution control.



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# MÉXICO

## Opportunities in Industrial Minerals

by

Armando Alatorre<sup>1</sup>, Peter Harben<sup>2</sup>, Hal McVey<sup>3</sup>, and Ken Santini<sup>4</sup>

### ABSTRACT

The Republic of México is the world's largest producer of celestite/strontium carbonate and natural sodium sulfate. It is also a significant producer of fluorspar, barite, graphite, sulfur, feldspar, salt and gypsum. New production may be brought on stream for borates, wollastonite, garnet, calcium carbonate and others.

The country covers a geographic area of approximately 2 million square kilometers (760,000 square miles), and is divided into seven geological/geomorphological provinces. Less than 20 percent has been explored in detail for either nonmetallic or metallic minerals. This leaves large areas available for the discovery of world-class industrial mineral deposits. In addition to new deposits of those minerals currently being produced, there is exploration and development potential for borates, magnesite, rare earths, nepheline syenite, heavy mineral sands and numerous others.

### INTRODUCTION

México has long been known as a treasure house of minerals, both metallic and nonmetallic. The development of these minerals has been somewhat delayed by political, financial and transportation factors. This situation is in a process of change which has again focused attention on México. For example, the Salinas de Gortari administration has undertaken a series of measures designed to help the Mexican mining industry from the standpoint of legislative, fiscal and administrative procedures. This paper takes a look at the potential for industrial mineral opportunities in the "new" México.

The country covers a geographic area of 1,973,000 sq km, or 762,000 sq mi. This area is equal to the combined size of Texas, California, Arizona, New Mexico and Nevada. There are seven geological/geomorphological provinces in 31 states plus the capital, Distrito Federal (Figures 1 and 2). More than 60% is mountainous, and it is believed that less than 20% has been explored in detail for either nonmetallic or metallic minerals. This leaves large areas available for the discovery of world-class industrial mineral deposits. In addition to new deposits of those minerals currently being produced, there is exploration and development potential for industrial minerals that are presently being imported, and could be produced in México.

México is the world's largest producer of celestite/strontium carbonate and natural sodium sulfate. It is the third largest producer of fluorspar; fourth of barite; fifth of graphite; seventh of sulfur and feldspar; eighth of salt and eleventh of gypsum. In addition, it is a significant producer of many others including phosphate rock, calcium carbonate, silica sand, bentonite, diatomite and perlite. New production may be brought on stream for borates, wollastonite, garnet, clays and others.

Based on its population of some 90 million and the average annual growth rate of 2.2%, there is a significant and growing domestic Mexican market for numerous industrial minerals. Because of México's geographic location, the United States also represents a market for its nonmetallics and additional export potential. Conversely, México is the destination for significant quantities of industrial minerals from the United States. México exports nonmetallics to other Latin American countries, as well as, to Europe and the Far East. Emerging domestic markets and export opportunities indicate a bright future for industrial minerals exploration, production and markets. Favorable changes in México's transportation, political and financial segments are expected to increase the facility for operating in México. This enhances the beneficial relationship that presently exists between the United States of México and the United States of America.

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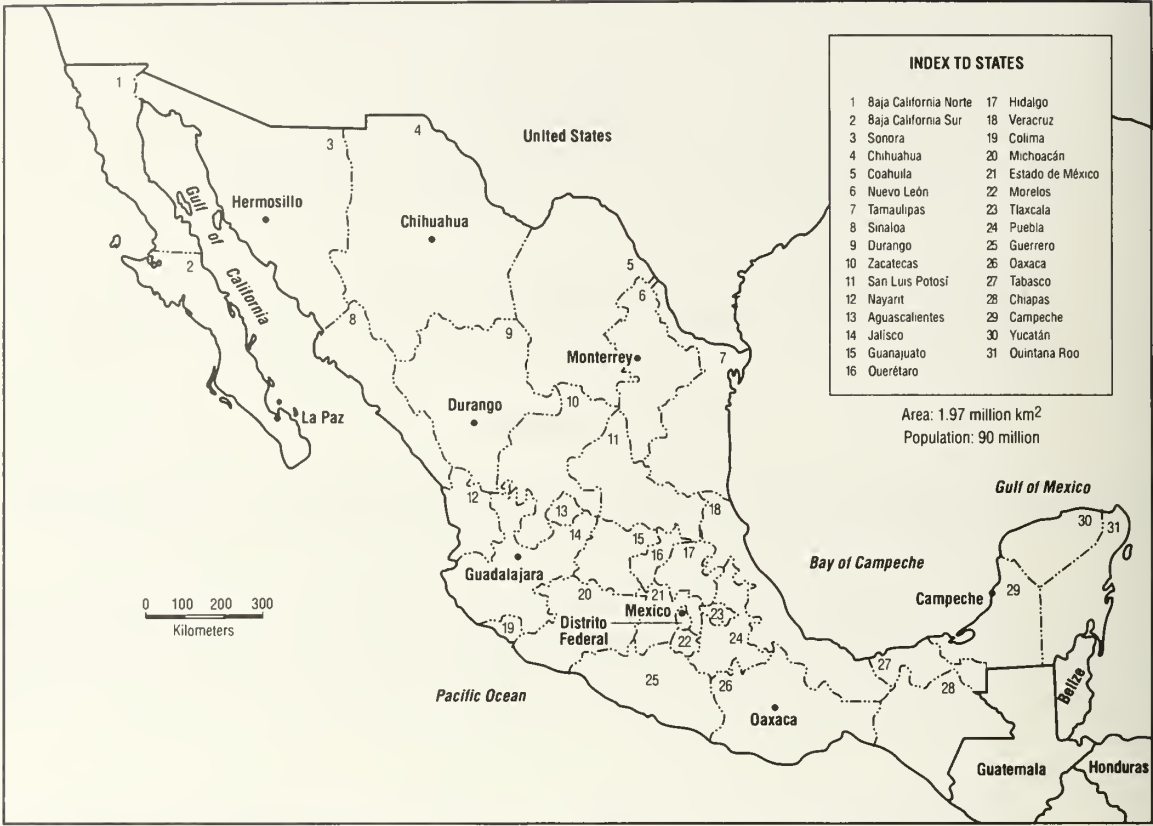


Figure 1. Index to Mexican states and selected cities.

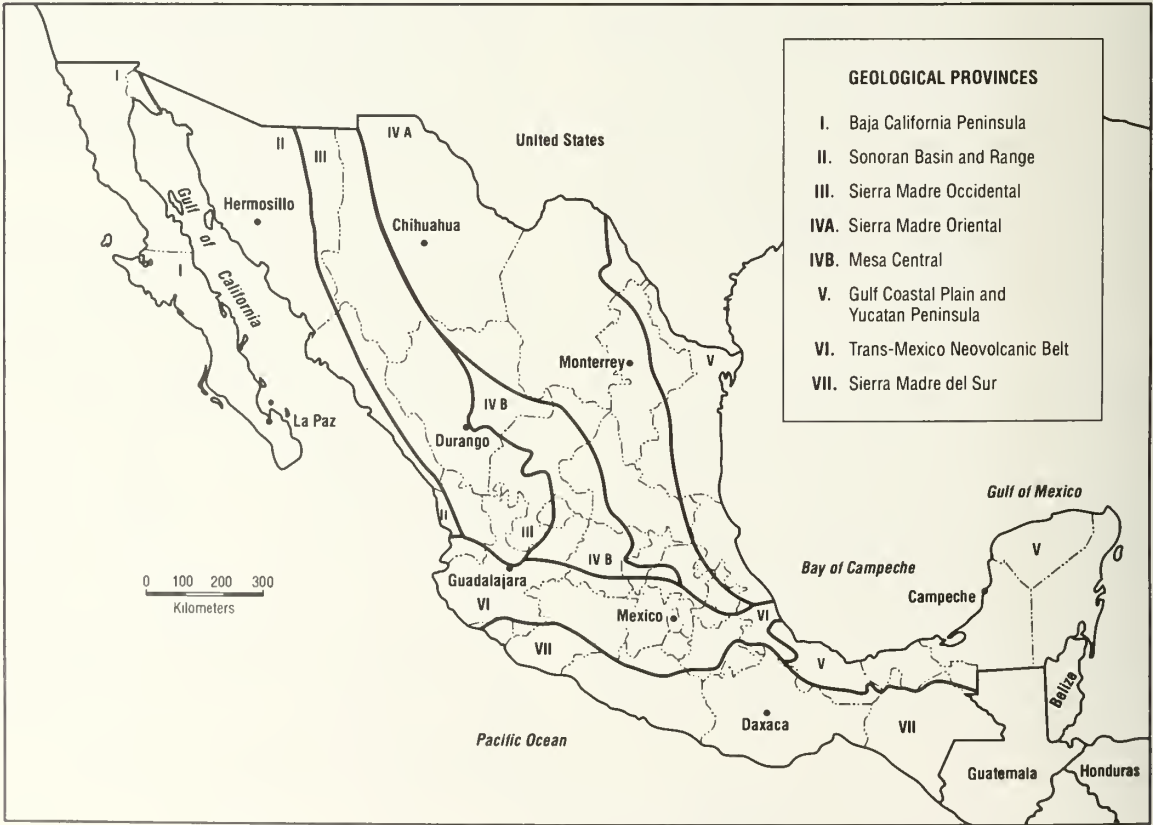


Figure 2. Mexican geological provinces



## HISTORY OF NONMETALLIC MINING

Mining of nonmetallic minerals in México dates back to at least 1000 BC, and probably millennia before. The Olmecs and all of the later pre-Columbia civilizations quarried and cut dimension stone, as evidenced by the famous and sophisticated pyramids, and surrounding structures in the southern half of the country. Clays have been mined, some from underground, and used for cosmetics and pottery for thousands of years. Numerous images and gods, fashioned from basalt, are found in ancient excavations. The well-known and complex Aztec calendar was carved from stone, which was mined probably about 800 years ago or more. Mining of flint and obsidian for tools and weapons, no doubt commenced as soon as humans arrived in México, many millennia in the past. Salt, which they mined in southern México, was used by the Mayans as a trading medium, before the birth of Christ.

Other than their utilization in construction, religious ceremonies, cosmetics and the making of tools for work and war, there was a long hiatus until nonmetallic minerals saw extensive use in México. In the post-Columbia era, the first mining for nonmetallics was probably in about 1580, when potassium nitrate was mined, and used in the processing of metallic ores. In 1800, sodium carbonate was employed in the smelting of base and precious metals.

Opals were discovered in the states of Hidalgo and Querétaro in the early 1850's. The latter resulted in the town of Querétaro giving birth to many artisans, who cut and polished opals, and later, stones from all over the world. Querétaro continues as one of the major gem-cutting centers in México and the world.

Notwithstanding the uses of nonmetallic minerals cited above, the true era that permitted their designations as "industrial minerals" in México, commenced after World War II. In rapid succession, sulfur was discovered in the Isthmus of Tehuantepec in 1945, and phosphate rock in Baja California Sur in 1946. Fluorspar was first mined in 1947, and barite in 1951. The Frasch process for sulfur extraction started in México in 1953, and salt was first produced, from the now-famous Guerrero Negro deposit in Baja California Sur, in 1954.

The 1960's and 1970's witnessed the start up and real growth of large industrial mineral ventures in México. Many of the ventures were in fluorspar, celestite, sodium sulfate, phosphate rock, barite, silica sand, feldspar and gypsum. The late 1970's and early 1980's was the period of the government's State Owned Mining Enterprise, which encouraged and financed mining ventures. The history of industrial mineral mining in

México, therefore, is fairly recent. For example, everyone associated with industrial minerals knows of the shipments of gypsum from San Marcos Island, located in the Sea of Cortez, Baja California Sur; to California, Oregon, Washington and British Columbia. It seems as though this mine must have been in operation for many decades, but it only began production in 1979.

In 1974, the government created the Fideicomiso de Minerales No-Metalicos Mexicanos (later called Fideicomiso de Fomento Minero). Two of the notable developments fostered by this agency were Barita de Sonora and Grafito de México, subsequently privatized. Another government agency, the Comision de Fomento Minero (no longer in existence with its duties assigned to the Consejo de Recursos Minerales and Fideicomiso de Fomento Minero), has invested in the development of mining, including nonmetallics, in México.

Demographical and political changes both in México and the world, indicate that a large increase in México's industrial minerals output or imports will have to be accomplished, in order to keep up with increasing demand.

## ORGANIZATIONS AND ADMINISTRATION IN MEXICO

This section addresses the governmental and non-governmental organizations that are of primary importance to the exploration and exploitation of industrial minerals in México.

### GOVERNMENTAL

#### Secretaría de Energía, Minas e Industria Paraestatal - SEMIP

As far as the day-to-day administration of mining is concerned, this organization is at the top of the governmental agencies. SEMIP regulates mining activities via the Under Secretary of Mining. Functions and administration of directives from SEMIP are carried out by two departments: Directorate of Mining and Metallurgical Operations, and Directorate of Mines.

#### Directorate of Mining and Metallurgical Operations

The existence of this department was at a zenith, when the State Owned Mining Enterprise grew from 1971 to 1982. This was an era of expansion under the so-called, "State Capitalism." Because of the process of privatization undertaken during the 1980's, and continuing into the 1990's, the government is now left with relatively few wholly, or partially owned mining companies, most notably in sulfur, phosphates and salt. It is reported that these remaining holdings are for sale.

The headquarters of this directorate mainly performs legal, financial and administrative duties. Personnel are composed largely of economists, lawyers and accountants. This directorate also has responsibility for three agencies — Consejo de Recursos Minerales, Fideicomiso de Fomento Minero and Directorate of Mines.

### **Directorate of Mines**

This agency administers the legal aspects concerning concessions and claims, in a relatively similar manner to the U.S. Bureau of Land Management. The Directorate of Mines was responsible for the conception, structuring and implementation of the new 1992 Mining Law (discussed under "Mining Law"), which has been adopted by the legislature. To a large extent, this is the Department that has defined the Mining Policy in México for a number of decades. Based on the Mining Law, they define whatever minerals or rocks are subject to control. This is a key aspect because some minerals and rocks, such as limestone, kaolin, marble, sand, gravel, various common clays, mineralized waters and other, are not ruled by the Mineral Law.

A considerable number of deposits of nonmetallic minerals are located on "ejido" lands. These agrarian communities have a unique legal dominion, somewhat similar to Indian lands in the United States. This legal exclusion from the Mining Law has been, and will continue to be, of considerable importance to the development of industrial minerals, not ruled by the Mining Law.

### **Consejo de Recursos Minerales**

The Consejo de Recursos Minerales (CRM) organization is somewhat similar to the U. S. Geological Survey. Exploration at local and regional levels account for a substantial part of the budget. It also has the responsibility for in-depth exploration for specific minerals, such as phosphate rock, sulfur, kaolin, potash and bauxite. This responsibility started when the State Owned Mining Enterprise was anxious to expand its operations. This type of activity is diminishing.

CRM also carries out duties comparable to the U. S. Bureau of Mines in that it collects, collates and distributes information and data from governmental and private mining firms. This information is published and is available to the public.

CRM also contracts to domestic and international mining firms for such work as geophysical, and aerial location and interpretation of anomalies. Or, for instance, the agency might effect a detailed exploration effort aimed at increasing the reserves of Frasch sulfur, on behalf of the state-owned mining company. There are four or five large

mining companies that control about 90% of México mineral output. Thus, the CRM assists in development having expertise and equipment available for medium and small companies.

### **Fideicomiso de Fomento Minero**

Fideicomiso de Fomento de Minero (FFM) is a trust (fideicomiso) for the development and encouragement (fomento) of mining. It is basically, a federal agency aimed at providing financial support to small and medium-sized mining concerns in México. Its support encompasses all minerals and rocks, whether or not ruled by the Mining Law.

Up until recently, the agency employed a large number of technical personnel, such as geologists and mining and metallurgical engineers. They also had technicians running 18 small concentration plants, strategically placed in various mining districts. The plants provided milling services to the small and medium-sized mining concern which, for whatever reason, could not have their ore processed by the larger mills. These operations were mainly associated with silver, lead and zinc production and were operated more as a service, than as profit centers. By 1990, FFM decided to divest these concentrators and they were either sold to private companies, or closed.

Prior to 1992, FFM also operated 8 mineral laboratories and testing facilities. These have been transferred to the Consejo de Recursos Minerales.

As noted under the section, "Mining Development," FFM still administers and finances ventures through matching-fund type programs under PRONASOL. This type of financing is similar to Canada's Minerals Development Program (MDP), whereby the provincial and federal governments put up matching funds for private companies that can demonstrate the probable economic value of mineral deposit. FFM type development is a valuable service in México, in that financing high risk mining ventures through a stock exchange, is not accepted like it is in the United States and, more especially, in Canada.

Initial contacts by foreign firms, at an entry level of interest in operating in México, would mainly be directed to the Consejo de Recursos Minerales. This agency provides maps, geological reports and other items similar to those available in the United States.

### **Instituto Nacional De Estadística, Geografía E Informática (INEGI)**

This National Institute For Statistics, Geography And Information offers topographic, geologic, land-use and other base maps as well as government-derived statistics relating to the mining industry.



## NON-GOVERNMENTAL

### La Camara de Minera de México

The Chamber of Mines of México is an organization comprised of medium and large mining companies, and others interested in mining. Within the chamber there are various groups of producers with special interests: non-ferrous; ferrous; nonmetallic; copper; and smelting and refining. It is structured like the American Mining Congress with the directors being from private industry, and a Director General, who is a full-time employee, with appropriate staff.

### Agrupación de Medianos Productores de Minerales de México

This is an organization consisting of a group of medium to small mineral companies. The members can be metallic or nonmetallic producers with the main theme being, to share areas of common interest and to promote these interests.

### Asociación de Ingenieros de Minas, Metalurgistas y Geólogos de México, A.C.

This organization is identical to, and serves the same function as, the Society for Mining, Metallurgy and Exploration (SME) in the United States, and the Canadian Institute of Mining and Metallurgy (CIM) in Canada. Meetings are held every two years in October, and the venue has been Acapulco (although they have been held once each in Guadalajara and in Mazatlán since 1975).

## MINING AND INVESTMENT LAWS

### Historical background

The basic concept of Mexican mining law has its roots at the beginning of the Spanish Colonial era of the Americas. The important tenants of the law are embodied in the Mexican constitution. The fundamental premises of the law are:

- The mineral estate is separate and distinct from the surface estate
- The mineral estate includes the right of eminent domain with respect to the surface estate, recognizing the right of the surface owner to due compensation for damages
- Title to the mineral estate is vested in the state and can not be alienated
- The state, and only the state, can award the right to extract or exploit the mineral estate to individuals or to legal entities

The Mining Law of 1961 required that the ultimate ownership of any new mining operation must be at least

51% Mexican owned. The law also established a procedure and time-frame for accomplishing this end. By 1980, the process was substantially completed. In addition to establishing the minimum ownership by Mexican individuals or corporations, the law defined broad areas of the country, which were judged to be favorable, for the occurrence of minerals, and these were placed within the National Mining Reserves (Zonas de Reserva Minera Nacional). Further and specifically, iron ore, coal, sulfur, phosphate and potash were deemed to be part of the National Mining Reserves by definition. Production of minerals from the National Mining Reserves was confined to companies that were at least 66% Mexican owned.

The Mining Law was modified in 1975, in respect to foreign investment. The net Mexican ownership of mineral ventures remained at 51%, and mineral concessions could only be issued to companies organized in México. Qualified companies could issue two different classes of shares:

- Class "A" shares, representing at least 51% of the capital, can only be held by Mexican nationals or companies; and
- Class "B" shares, representing not more than 49% of the capital, can be held either by Mexicans or foreign nationals or companies. In the case of National Mineral Reserves, class "B" shares must represent not more than 34% of the capital, and the state must own an interest in the company.

Under the Code of Regulations of 1990, companies with less than 51% Mexican ownership are permitted to hold concessions, provided that an investment trust (fideicomiso), to hold the Class "A" shares, be established with a Mexican bank or a fiduciary organization. The trustee for foreign investors, can hold these Class "A" shares for a defined period of time, after which the Class "A" shares must be sold to Mexican investors.

The allowable duration of the trust, for holding the Class "A" shares, varies with the nature of the company and the investment. If the company is engaged only in exploration, or if the investment is in the shares of an existing company, and has been approved by the National Commission on Foreign Investment, the life of the investment trust may be as long as 30 years. In the case of a company that explores and develops a mine, the trust may last for an exploration period of up to 6 years, plus 13 years from the day of first commercial production.

### Present law

A new Mexican Mining Law (Ley Minera) was promulgated by the Mexican Congress in 1992. The law regulates article 27 of the Constitution and is to be enforced by the Federal Executive Branch, through the Secretaría de Energía,



Minas e Industria Paraestatal (SEMIP). Copies of the "Ley Minera" or "Mining Law" are available from SEMIP in México D. F., and there is an English translation. Needless to say, any company doing business in México would want to retain local counsel for interpretation of the law.

Exploration concessions have a non-renewable life of six years. Exploitation concessions are for 50 years, and can be renewed for an additional 50 years. The annual tax on lands for exploration is \$5,000 old pesos or N\$5.00 per hectare, or about US\$0.67 per acre. For exploitation, the tax is \$22,000 old pesos per hectare for nonmetallic minerals, or approximately US\$2.97 per acre.

Normal annual taxes consist of a corporate tax at 35% and a minimum tax of 2% on fixed assets. The fixed assets tax can be credited against corporate taxes, which diminishes its effect to some extent. This tax has been designed for those companies which have a positive cash flow, but a negative taxable income. The annual tax on lands is indexed to inflation.

Although not technically a tax, all companies must distribute a 10% profit sharing tax to employees. The profit sharing is calculated on taxable income.

In addition to visible taxes and defined benefits, it is common for the mining company to create and maintain infrastructure for remote mining communities, and to provide community and social benefits, such as schools, medical care, etc. It should also be noted, that there are definite regulations which govern the termination of an employee after he/she has worked for the company for a certain minimum period of time, usually one year.

### Encouragement of mining

The government of México has made several changes in order to improve the economy of the country, among these have been the revisions of the Mining Code in 1990, and the Mining Law in 1992. It is reported at the time of the writing of this paper, that a new "Code Of Regulations" is being published. These changes have been aimed at:

- Modernizing the country's industry;
- Promoting mining activity and investment;
- Increasing the contribution of mining in economic development; and
- Optimizing the exploitation of mineral resources.

The most important changes in the law have been to:

- Define the extent of the law more clearly;
- Reduce government participation in exploration and production; and
- Reduce the organizational procedures for attaining exploration and exploitation rights.

For example, it has historically taken up to five years to attain a mining claim. Through the utilization of computers and with better organizational procedures, the period is now down to less than one year.

### Industrial minerals

Some of the major items in the 1992 Mining Law that are pertinent to the industrial minerals sector are outlined below. The English translation of "Mining Law" states:

#### Article 2.

The exploration, exploitation and processing of minerals or substances that constitute deposits in veins, masses or beds which differ from land constituents shall be subject to the provisions of the Law herein.

#### Article 3.

The following terms shall have the meaning hereafter stated for the purposes of the subject Law.

**I. Exploration:** The works and labor executed in the land in order to identify mineral deposits, as well as to quantify and to assess the economically profitable reserves that it may contain.

**II. Exploitation:** The works and labors aimed at the preparation and development of the areas comprising the mineral deposit, as well as those intended for detaching or extracting the mineral products existing in the same, and,

**III. Processing:** The works for the preparation, treatment, primary smelting and refining of mineral products, at any stage, in order to recover or to obtain minerals or substances, as well as to raise the concentration and purity of their contents.

#### Article 4.

Article 4 designates the Mineral Estate into eight classes:

- I Metallic elements - Not listed in this paper.
- II Industrial minerals - See Mineral Estate Status (Table)
- III Rare earths.
- IV Mineral gems.
- V Rock salt and any salt obtained from sea water on the surface or underground, by natural or artificial methods.
- VI Products derived from the decomposition of rocks which may be exploited mainly through underground works, such as kaolin and montmorillonites, as well as quartz and feldspar sand and plagioclases.
- VII Mineral or organic matter used as fertilizers.
- VIII Fuels: anthracite, mineral coal, lignite and peat.

Table 1. Mineral estate industrial minerals.

<b>Asbestos Group</b>	<b>Corundum</b>	<b>Potassium Group</b>
Actinolite	<b>Cordierite</b>	Carnallite
Anthophyllite	<b>Diatomite</b>	Kainite
Chrysotile	<b>Dolomite</b>	Langbeinite
Tremolite		Silvite
<b>Sillimanite Group</b>	<b>Fluorite</b>	<b>Precious Stones</b>
Andalusite	<b>Glaserite</b>	<b>Pyrophyllite</b>
Kyanite	<b>Graphite</b>	<b>Quartz</b>
Sillimanite	<b>Garnet</b>	<b>Rare Earths</b>
<b>Barite Group</b>	<b>Gypsum Group</b>	<b>Sodium Group</b>
Barite	Gypsum	Bloedite
Witherite	Anhydrite	Epsomite
<b>Alumina Group</b>	<b>Inderite</b>	Mirabilite
Alunite	<b>Magnesium Group</b>	Polyhalite
Bohemite	Brucite	Salt
Diaspore	Hydromagnesite	Sodium Nitrate
Gibbsite	Kieserite	Thenardite
<b>Borate Group</b>	Magnesite	Trona
Boracite	<b>Mica Group</b>	<b>Sulfur</b>
Borax	Muscovite	<b>Strontium Group</b>
Colemanite	Phlogopite	Celestite
Sassolite		Strontianite
Durmortierite	<b>Phosphate Group</b>	
Howlite	Apatite	<b>Talc</b>
Inyoite	Colophane	<b>Titanium</b>
Priceite	Francolite	<b>Vermiculite</b>
Sussexite	Phosphate Rock	<b>Wollastonite</b>
<b>Clay Group</b>	Variscite	
Palygorskite	Wavelite	<b>Zircon</b>
Sepiolite	Vivianite	

## SURFACE ESTATE INDUSTRIAL MINERALS

Note: These minerals are not specifically designated in the 1992 Mining Law but it appears as though they are excluded from the Mineral Estate minerals.

### Building Materials

Aggregates  
Dimension Stones  
Sand and Gravel

### Clay Group

Kaolinites  
Montmorillonites

### Fieldspars

### Silica Sand

Item VI of Article 4 seems to state that clays, silica sand and feldspars are part of the Mineral Estate only when exploited by underground workings, which almost never occurs.

### Article 5.

The following are excepted from the applicability of the Law herein:

- I Petroleum, etc.
- II Radioactive materials.
- III Substances contained in suspension or dissolution by underground waters, provided their source is not a mineral deposit from land constituents.
- IV Rocks or products from its decomposition that could only be used to manufacture construction materials or be intended for such use.
- V Products derived from the decomposition of rocks where exploitation is primarily effected through open pit works.
- VI Salt from salt pits formed in endorheic basins.

Item IV seems to exclude certain industrial minerals, such as aggregates, all of the dimension stones, and sand and gravel, from the Mineral Estate. Item V of Article 5 seems to state that clays, silica sand and feldspars are not part of the mineral estate, if they are exploited by open pit mining, which is almost always the case. Minerals not in the "Mineral Estate" are said to be in the "Surface Estate", and the latter are treated differently and are not, therefore, administered by SEMIP.

The "Surface Estate" industrial minerals are listed in the same table (Table 1) as the "Mineral Estate" industrial minerals. Surface estate minerals are subject to control of land owners, private or ejidos. "Ejidos" or "ejiditarios" are communal agricultural lands governed by a form of municipal council. Ejidos have always had the right to rent or lease their lands and as of the end of 1991, ejidos are now permitted to sell their lands. In the case of surface estate minerals, foreign investment is subject to less strict procedures and 100% foreign ownership is possible.

One of the most significant changes that affects the industrial minerals sector in the 1992 Mining Law, is that the National Mining Reserves (Zonas de Reserva Minera Nacional) by definition were eliminated. This allows the exploration and exploitation of sulfur, phosphate and potassium minerals. Also, over 3 million hectares, or, about 8 million acres have been released into the public lands, which are now concessionable by mining companies. There is also the possibility of attaining exploration and production rights for minerals on the continental shelf; this would be through a bidding process.

## Conclusions

Foreign companies can invest and participate in exploration and exploitation of governmental concessionable mineral deposits, through investment trusts (fideicomiso) with 100% ownership. If an investment trust is not used as a vehicle the foreign entity is limited to 49% ownership and many ventures are structured with the Mexican company or individual owning 60% and the foreign investor holding 40%, however, the allocation of investment funds is not necessarily in that ratio.

The fact that the 1992 Mining Law does not state any constraints on foreign investment, as did the 1961 and 1975 laws, is considered as the first step forward in eliminating strict foreign investment regulations for the mining industry.

## MINING DEVELOPMENT

The Salinas de Gortari administration has instituted two progressive programs entitled, Programa Nacional de Modernización de la Minería 1990-1994 (PRONASOL) and Programa Nacional de Solidaridad (Solidaridad). The programs are dedicated to the encouragement and development of small and medium-sized mining companies.

As part of the PRONASOL program, the federal government has released 3,258,187 hectares (8,050,870 acres) into the public lands, which are now concessionable to mining companies. Examples of encouraging (fomenting) mining activities are:

In the 1991-1994 program for the development of mining in the northern sector of the state of Coahuila, the Fideicomiso (investment trust) de Fomento Minero (FFM) set up a program whereby mining companies would invest about US\$32,000,000 and FFM would grant credits of US\$53,000,000, or a total of about US\$85,000,000, for the development of minerals. These include such industrial minerals as fluorite, dolomite, gypsum, celestite, silica sand, barite, calcium carbonate and feldspars.

In the state of Sonora, the PRONASOL program calls for industry to put up about \$36,000,000 and FFM approximately \$60,000,000, a total of \$96,000,000, for the development of minerals. Examples include graphite, limestone, salt, clays, perlite, wollastonite, zeolites, borates, sodium carbonate, barite and gypsum.

During the last few years, the government has been privatizing some of their mines. For example, Grafitos de México, which was started under the old Fideicomiso de Minerales No-Metalicos, was purchased in 1989, by Minerales Mexicanos No-Metalicos, S.A., a private company. The government also has offered, or is going to offer, for sale the following: Exportadora de Sal (salt), Roland Fosforica (phosphate), Azufrera Panamericana (sulfur) and Cía. Exploradora de Istmo, S.A. (sulfur).



## GEOLOGICAL PROVINCES

In geological terms, México is relatively young, being underlain for the most part by sedimentary and volcanic rocks of Mesozoic to Cenozoic age. These rocks have been thrust up, or built up in the case of some volcanics, into a generally rugged and mountainous terrain. This intense tectonic and magmatic activity has given rise to widespread mineralization, and the country is particularly well endowed with those types of deposits, which form close to the earth's surface in tectonically active areas.

As illustrated in Figure 2, the country can be divided on the basis of topography and general geology, into seven relatively distinct geological/geomorphological provinces (Salas, 1975). A more recent study, divides the country into 35 geological provinces (Ortega-Gutiérrez, *et al.*, 1992). See Table 2. Based on this detailed study, two main characteristics are recognized. The first, as mentioned previously, Mexican geology is young. About 75% of the provinces are Mesozoic or Cenozoic in age, and approximately 12% Precambrian in age. Secondly, the eastern half has been a passive margin since the Jurassic, and thus, is mainly sedimentary. The western half, being a convergent margin since about the same time, is mainly igneous and metamorphic. For the purpose of discussing México's industrial minerals and potential for locating and developing new deposits, only the seven general geological provinces will be reviewed. From northwest to southeast, the provinces are:

- Baja California Peninsula
- Sonoran Basin and Range
- Sierra Madre Occidental
- Sierra Madre Oriental and Mesa Central
- Gulf Coastal Plain and Yucatán Peninsula
- Trans-Mexico Neovolcanic Belt
- Sierra Madre del Sur

### Baja California Peninsula

Baja California, also known as Lower California, is a peninsula approximately 1,300 km long and 75 to 150 km wide. It extends southwesterly from the border with the United States, and is separated from the rest of México by the Gulf of California and the delta of the Colorado River.

The northern portion of the peninsula is underlain by metasedimentary and metavolcanic rocks, which range in age from Precambrian to early Mesozoic. They have been intruded by numerous small plutons, that range from granite to gabbro in composition, and are overlain by late Cretaceous to early Tertiary sediments and volcanic rocks. The central portion of the peninsula is underlain by intercalated volcanic and sedimentary rocks in the east, and a

sedimentary-volcanic complex with ophiolitic affinities in the west. These rocks are overlain by mildly deformed Tertiary sedimentary rocks, including Miocene phosphorites and volcanic rocks. From the 28° parallel to the south, the geology consists of a pile of extrusive rocks, predominantly andesites and andesitic tuffs associated with some intrusive rocks. The latter occur south of Santa Rosalia, in the Sebastian Vizcaino Bay area, and near the La Paz Bay area. The southernmost portion of the peninsula is underlain by a granitic batholith of apparent Cretaceous age, which is flanked by metamorphic rocks, and overlain by Tertiary pyroclastic and clastic sedimentary rocks. Late Tertiary to Quaternary volcanic rocks occur in several places on the peninsula.

The Baja California Peninsula started forming during the middle Cretaceous. Subduction caused andesitic volcanism from Arizona to south of the State of Sinaloa. At the end of the Cretaceous, the peninsula began to move, as a block, towards the northwest. At the start of the early Tertiary, it became separated from the continent, giving rise to a proto-Gulf of California. The present geomorphology of the peninsula began to develop between 4 - 6 million years ago. There is evidence from Miocene sediments, at Tiburon Island and elsewhere, of the existence of the incipient Gulf before the Miocene, although not in its present form.

The major industrial minerals in the Baja California Peninsula Province are: salt (by solar evaporation) at Guerrero Negro, gypsum from San Marcos Island in the Gulf of California, and Oligocene-Miocene phosphate rock at San Juan de la Costa.

### Sonoran Basin and Range

The province is the southern extension of the Basin and Range Province of the southwestern United States. It is about 350 km wide on its northern end, and pinches down to a narrow coastal strip on its southern end. Basement rocks are Precambrian metamorphics and intrusives. These are overlain by a relatively thin sequence of late Precambrian to Mississippian quartzite, sandstone, limestone and dolomite. The Precambrian and Paleozoic rocks are overlain, in turn, by Triassic clastic sedimentary rocks, which contain thin coal seams, and Jurassic to Cretaceous sedimentary and volcanic rocks. The entire sequence has been folded and intruded by numerous granitic stocks. Tertiary volcanic rocks, comprised of a lower andesite series and an upper rhyolite series, overlie most rocks in the province. Some Quaternary volcanics are present in the western part of the province. Tertiary block faulting formed the basin and range topography of the region.

Major industrial mineral deposits include amorphous graphite and barite, both located southeast of the city of Hermosillo.

Table 2

Geological province	Age	Origin	Tectonics
1 Yucatan Platform	Cenozoic	sedimentary marine	platform
2 Tabasco deltaic basin	Cenozoic	sedimentary continental	geoclinal
3 Chiapas folds/faults	Cenozoic	sedimentary marine	orogenic
4 Chiapas batholith	Paleozoic	plutonic	arch roots
5 Sononuscos igneous massif	Cenozoic	plutonic	arch roots
6 Tehuantepec basin	Cenozoic	sedimentary marine	geoclinal
7 Veracruz deltaic basin	Cenozoic	sedimentary continental	geoclinal
8 Tuxtla volcanic massif	Cenozoic	volcanic	continental arch
9 Cuicateca	Mesozoic	volcanosedimentary	submarine arch
10 Zapoteca	Precambrian	complex	complex
11 Mixteca	Paleozoic	complex	complex
12 Chatina	Mesozoic	plutonic	arch roots
13 Juchateca	Paleozoic	volcanosedimentary	submarine arch
14 Morelos platform	Mesozoic	sedimentary marine	platform
15 Transmexican volcanic belt	Cenozoic	volcanic	continental arch
16 Colima-Guerrero orogenic complex	Mesozoic	volcanosedimentary	submarine arch
17 Jalisco batholith	Mesozoic	plutonic	arch roots
18 Palma Sola igneous massif	Cenozoic	volcanic	continental arch
19 Gulf of Mexico geoclinal	Cenozoic	sedimentary marine	geocline
20 Mexican folds and faults belt	Mesozoic	sedimentary marine	orogenic
21 Coahuila platform	Mesozoic	sedimentary marine	platform
22 Zacatecana	Mesozoic	complex	complex
23 Valles-San Luis Potosi platform	Mesozoic	sedimentary marine	complex
24 Mexican ignimbrite belt	Cenozoic	volcanic	continental arch
25 Sinaloa orogenic belt	Mesozoic	volcanosedimentary	submarine arch
26 Chihuahuaense	Ceno-Mesozoic	complex	complex
27 Nayarit basin	Cenozoic	sedimentary marine	geocline
28 Sonora-Sinaloa deltaic basin	Cenozoic	sedimentary continental	geocline
29 Sonorense	Precambrian	complex	complex
30 Colorado river delta	Cenozoic	sedimentary continental	geocline
31 San Pedro Martir batholith	Mesozoic	plutonic	arch roots
32 Vizcaino-Purisma basin	Cenozoic	sedimentary marine	geocline
33 Cedros-Margarita orogenic belt	Mesozoic	volcanosedimentary	subduction complex
34 La Giganta volcanic belt	Cenozoic	volcanic	continental arch
35 La Paz plutonic complex	Mesozoic	plutonic	arch roots

## Sierra Madre Occidental

This province extends along the United States-México border from the town of Sasabe, Sonora, to the vicinity of Estacion Palomas, Chihuahua, and southward to near Guadalajara, Jalisco. It is about 1,300 km long and approximately 200 - 300 km wide, with an areal extent of more than 275,000 sq km. Elevations range from 1,500 to over 3,000 m.

Basically, the province is a long anticlinal volcanic plateau with steep westerly dips, and more gentle easterly dips. The volcanic rocks of the province consist of a "Lower Volcanic Complex", composed of andesitic volcanics and

batholithic intrusives, having radiometric ages of 100 to 4 million years before the present. The andesitic volcanics rest on Precambrian, Paleozoic, and Mesozoic metamorphic and igneous rocks, and remnants of some sedimentary rocks. In addition, there is an "Upper Volcanic Suite" group of rhyolitic composition, comprised of ignimbrites, with associated mafic lavas, displaying radiometric ages of 34 to 23 million years. The entire region has been cut by longitudinal faults and is highly dissected by erosion.

The rugged topography and consequent difficulty of access, have limited exploration and impeded development of the industrial mineral resources of the region.



## Sierra Madre Oriental and Mesa Central

The Sierra Madre Oriental extends southeasterly for about 1,300 km from the border with the United States, south to the Trans-Mexico Neovolcanic Belt. Lying between the Sierra Madre Oriental and Sierra Madre Occidental Provinces, is the wedge-shaped Mesa Central. Some workers treat the Mesa Central as a separate province, but Cserna (1989) includes it as part of the Sierra Madre Oriental based on geological evidence. The Sierra Madre Oriental and Mesa Central have a combined width of 400 to 500 km, and an average elevation of about 1,500 m.

Precambrian metamorphic rocks crop out at a few locations in the province. However, the distinguishing geological feature of the Sierra Madre Oriental region is a thick sequence of Permian and lower Mesozoic carbonate rocks, separated by an intervening section of Triassic continental red beds and volcanic rocks. These Paleozoic and Mesozoic sedimentary and volcanic rocks have been subjected to complex folding and thrust faulting, and are cut by numerous granitic stocks of Eocene age, which, in turn, are overlain by Miocene volcanic rocks. The entire sequence (greater than 3,500 m thick), has been broken by Tertiary to Quaternary block faulting, giving rise to typical basin and range topography, and is overlain by scattered occurrences of very young basaltic flows.

The Mesa Central region contains a volcanic pile of middle to late Cenozoic age lava flows, breccias, tuffs and agglomerates, which range in composition from basalt to rhyolite. The latter is more abundant, north of the city of Querétaro. Near the cities of Zacatecas and Fresnillo, the volcanic pile is intruded by granodiorites. The geology of the region comprises part of the Sierra Madre Oriental sediments, which probably underlie the area's predominant volcanic sequence. For example, due to erosion and tectonism, a basement of Mesozoic sediments, similar to those that occur in the Sierra Madre Oriental, outcrop northeast of the city of Aguascalientes. In other areas, such as near Guanajuato, there is a Mesozoic metamorphic basement.

The Sierra Madre Oriental is perhaps the most intensely mineralized region of Mexico, both for industrial minerals and metallics. Significant fluorspar deposits tend to be concentrated in (1) the northern portions of the State of Coahuila and (2) the States of San Luis Potosí and Guanajuato. The important celestite deposits, along with some of the larger barite deposits, occur in the same general geological settings in the northern and eastern portions of the province. Sodium sulfate is produced from a brine deposit at Laguna del Rey in Coahuila. Magnesium chloride is a co-product from that operation. Dolomite for steel- and glass-making is obtained from the calcareous section between Monterrey, Nuevo León and Monclova, Coahuila. The province is the site of bedded gypsum

deposits in Nuevo León and San Luis Potosí. In addition, Jurassic diapiric salt is solution-mined as a feedstock for synthetic soda ash production, north of Monterrey, Nuevo León.

Industrial minerals produced from Mesa Central, include the contact metamorphic wollastonite deposits in the Panfilo Natera area, northeast of the city of Zacatecas.

## Gulf Coastal Plain and Yucatán Peninsula

This province is comprised of mostly Tertiary sedimentary rocks, which overlie deformed, and metamorphosed Paleozoic and Mesozoic rocks. The Tertiary sedimentary rocks are of a clastic character in the region bordering the western Gulf of México, and are generally calcareous in the Yucatán Peninsula. These sedimentary rocks have been subjected to mild folding and faulting. In addition, they have been cut by alkalic intrusive rocks, as well as by numerous dikes and plugs, that were feeders for the basaltic lavas found in the province.

A major industrial mineral of the Gulf Coastal Plain is Frasch sulfur from salt domes south of Coatzacoalcas, Veracruz, and in the Isthmus of Tehuantepec. Silica sand for glass and foundry end-uses is obtained from Tertiary sedimentary units at the northern part of the province, near the United States-México border, as well as in the area near Jáltipan, Veracruz. A very large quarry, which supplies construction aggregate to U.S. ports on the Gulf of México, has recently been developed at Playa del Carmen, Quintana Roo, in the limestone units of the Yucatán Peninsula. Magnesia is the principal product from the seawater plant at Ciudad Madero, Tamaulipas.

## Trans-Mexico Neovolcanic Belt

This is a zone of extensive Tertiary to Quaternary volcanic rocks with numerous cinder cones and stratovolcanoes, many of which are presently active. The active volcanoes include México's highest peak, Pico de Orizaba (5,675 m), the famous Popocatepetl near México City, and the very young (1943) Paricutin volcano in Michoacán. Three main volcanic facies have been identified in the province. The oldest is a Cretaceous andesitic series with pillow lavas, breccias and tuffs interfingered with late Jurassic to early Cretaceous sediments, which were metamorphosed during the middle Cretaceous. Some outcrops of this facies are located in the Maravatio-Zitacuaro region in the State of Michoacán. The second facies, from the Oligocene-Miocene, occurs mainly on the western end of the belt, and is composed of breccias and lava flows that generally form mesas. The third facies, from the Pliocene-Quaternary and the one most extensive, has formed hundreds of cinder cones and related lava flows, as well as pyroclastic build-ups, and is predominantly andesitic in composition (Lopez-Ramos, 1979). In addition, many lacustrine basins, some of which may be hundreds of sq km



in size, are filled with pyroclastic derived material, and are present throughout this province. The western end of the province represents a pre-Cretaceous metamorphic basement, that was intruded by Cretaceous granitic stocks. Similar basement rocks are also reported as far inland as Taxco, Guerrero. Basement rocks, elsewhere, underlying the younger volcanics are similar to those in the geologic provinces, which adjoin the volcanic belt.

Industrial minerals produced in this province include the sodium carbonate brines from Lake Texcoco at the northern edge of México City, and freshwater diatomite near Guadalajara, Jalisco. Acid activated clays have been produced in the Tlaxcala area since about 1966. Lava flows and pyroclastic materials have been used as construction materials since pre-Columbus times. Semi-precious stones, mostly opal, are produced from pyroclastics in the Magdalena area, northern Jalisco, as well as near San Juan del Rio, Querétaro.

### Sierra Madre Del Sur

The province borders the Pacific Ocean, and adjoins the southern edges of the Trans-Mexico Neovolcanic Belt, Gulf Coastal Plain and Yucatán Peninsula Provinces. Basement rocks, in the portion west of the Isthmus of Tehuantepec, are Precambrian granulite facies metamorphic rocks, and Paleozoic schists, slates and gneisses. East of the Isthmus, the principal basement unit is a large pre-Mesozoic granite batholith. Overlying the basement rocks are early Mesozoic clastic sedimentary rocks, some of which contain coals, followed by younger Mesozoic carbonate rocks in the eastern part of the province, and volcanic or volcanoclastic rocks in the western part. The Mesozoic and older rocks have been folded and faulted, and have been intruded by late Cretaceous granitic stocks. The province was then subjected to block faulting and Tertiary andesitic volcanism, which is almost ubiquitous throughout México.

Major industrial mineral deposits of the Sierra Madre del Sur include: the La Minita volcanogenic massive sulfide-barite deposit at Coalcomán, Michoacán, as well as the crystalline (flake) graphite that is mined from Precambrian granulite facies metamorphic rocks at Telixtlahuaca, Oaxaca, and the gypsum deposits south of Acatlán, Puebla.

### Potential for Industrial Minerals

Exploration efforts made since the 1940's, have resulted in the discovery of industrial minerals, which were not known to exist in certain areas of México before that time. Some examples include: the Oligocene-Miocene phosphate rock in Baja, flake graphite in Oaxaca, as well as borates, thenardite and zeolites in Sonora. More than 60% of Mexico is mountainous, and it is believed that less than 20% has been explored in detail for either industrial

minerals or metallics. This leaves large areas available for the discovery of world-class industrial mineral deposits.

The following is an overview of selected areas in México that currently produce industrial minerals, and others that contain potential economically viable industrial mineral deposits (Figure 3). For the latter, major exploration and evaluation programs remain to be completed. Industrial mineral deposits are also discussed in the market section.

## Baja California Peninsula

### Phosphates

The State of Baja California Sur contains the most important source of phosphate rock in México. The deposits occur within the upper section of the late Oligocene to early Miocene marine Monterrey Formation. Phosphate beds crop out at three localities: (1) San Juan de la Costa on the Gulf of California side; (2) San Hilario, about 10 km north of La Paz and (3) the San Carlos area on the Pacific side. In addition, the lower section of the Pliocene Salada Formation, and the Pleistocene to Holocene beach deposits at Santo Domingo on the Pacific shoreline, contain phosphate deposits. Phosphate sedimentation has also been reported from the continental shelf off the west coast of the province. To date, the Monterrey Formation has been the only major source of phosphate rock production. The mine and processing operation is located at San Juan de la Costa, about 57 km northwest of La Paz.

The Monterrey Formation consists predominantly of fine grained sediments, that were deposited with almost no lateral variation during a slow marine transgression, and represents intertidal to outer shelf low energy environments. Deposition took place during late Oligocene to early Miocene time, as evidenced by radiometric, diatom and foraminiferal data.

Stratigraphically, from bottom to top, the Monterrey section is composed of (1) a phosphatic-volcanic conglomerate unit; (2) a tuff unit having two diatomaceous facies at different stratigraphic levels, as well as a phosphatic facies and (3) a widely distributed siliceous shale unit, having a calcareous facies and a phosphorite facies. Maximum thickness of the Monterrey Formation in the San Hilario area is 103 m, being thinner toward the southeast. In the San Juan de la Costa area, the total thickness is not known, because the base of the Monterrey is unconformably overlain by Holocene beach deposits.

Gradually decreasing volcanic activity, from the Mexican mainland to east of the Monterrey basin, contributed most of the material that constitutes the lower half of the Monterrey. Sporadic tuffs in the upper half of the Monterrey and volcanic material in the phosphate beds, indicate times of minor increases in volcanic activity during deposition of the upper half. Pulses of cold and warm ocean

waters, derived from the north and central Pacific, characterized the Monterrey basin, as evidenced by the occurrence of several diatom species, as well as planktonic and benthonic foraminifera. The distribution of diatom beds also indicates that the water temperature was slightly warmer on the east side of the basin at San Juan de la Costa.

At San Juan de la Costa there are eight phosphate rock horizons ranging in thickness from 0.15 to 2.00 m. The Humboldt bed has been the major source of production, and has been mapped in a 25 sq km area. It displays an average thickness of 1.9 m and an average grade of 19.6%  $P_2O_5$ . Initial mining was by open pit, however, because of an increasing stripping ratio, a modified room and pillar underground method with continuous miners is now employed.

There are two main phosphate beds at San Hilario. The upper unit is about 1.2 m thick, very consistent along strike for more than 25 km and grades 16%  $P_2O_5$ . The lower unit is about 0.8 m thick and continuous for more than 35 km, grading about 10%  $P_2O_5$  (Ojeda, 1991). However, the high calcareous matrix in both units has, thus far, prevented the production of a commercially acceptable product.

#### Other minerals

Based on a preliminary evaluation of heavy minerals in the San Antonio del Mar beach area, approximately 120 km south of Ensenada, a resource of about 130 million tonnes of fine and medium grained, well-sorted sand has been outlined. The sand is 13 m thick, containing about 12% heavy minerals, of which 4-6% is ilmenite and 0.2% zircon (Martin and Maruri, 1988).

Within the Vizcaino-Purísima Iray Basin, Baja California Sur, there are several Tertiary units containing marine diatomite beds, that have not been evaluated to date. They occur in the Tortugas and the Monterrey Formations. Barite, magnesite and talc deposits are also located in this province.

### Sonoran Basin and Range

The State of Sonora is probably the only state in Mexico that has a published inventory of its industrial mineral resources, from barite to zeolites (González, 1985), with numerous localities indicated, as well as references. Similar to this is an inventory of the mineral resources of the State of Sinaloa. It is mostly oriented towards metallic deposits, but includes some data on industrial minerals (Bustamante, 1986).

### Graphite

The graphite and coal districts of Sonora occur in the south central portion of the state, to the southeast of the city of Hermosillo. This region consists of mountain ranges that trend northwest-southeast, and are a continuation of the Basin and Range Province of the southwestern United States. Lithologically, the rocks consist of limestone, shale and quartzite of Paleozoic age. Thick accumulations of non-marine, and nearshore clastic sediments of Triassic and Jurassic age, also occur. Cretaceous through Tertiary age clastic sediments are present, in addition to a thick sequence of silicic to intermediate volcanics.

The late Triassic Barranca Formation contains coal seams, and at least seven amorphous graphite horizons. The Barranca is a thick sequence of light to medium colored quartzite, dark gray to black carbonaceous quartzite, conglomerate, coarse grained light colored sandstone, carbonaceous shale, dark colored carbonaceous mudstone, and coal. Where tightly compressed, and subjected to heat and pressure by tonalitic intrusives, the Barranca has undergone Tertiary (?) metamorphism. This has altered the coal to graphite, in areas up to 2,500 m around the intrusives, and in some locations has squeezed the graphite into faults. In certain areas, these metamorphic rings also contain sillimanite, kyanite, andalusite and K-feldspar, that have not as yet been exploited. The graphite beds vary greatly in thickness, due to the tectonic stresses and intrusives that affected the area. Thickness variations, between a few cms and 3 or 4 m, are not uncommon in short distances within a single mine. Graphitic carbon content is about 80%.

### Barite

Sedimentary barite deposits in Sonora occur in three areas southeast of Hermosillo. They are known as the Mazatán, Cobachi and San Jose de Moradillas areas. A detailed stratigraphic study of these three areas has defined nine sedimentary units that range in age from late Ordovician through late Permian. The areas can be readily correlated, and their differences in barite content are due to separate basins of deposition. The barite deposits are contained within Units 4, 5 and 6. Unit 4 is comprised of calcarenite, chert, sandstone, shale, limestone and siltstone. Barite at Mazatan is of higher quality and more nodular than at Cobachi, which is more sandy. Unit 5 consists mainly of black chert at Cobachi, and light colored chert at Mazatan, although at this later site, there is a black chert with rosette barite. Unit 6 is comprised of sandy barite, and barite nodules in shales and siltstones.

For the most part, the barite horizons are thicker at the bottom of each unit, thinning upwards in the section. The Mazatán barite has a higher specific gravity than the barite at Cobachi. This is probably due to more intense silicification at Cobachi.



## Saline minerals

Northwest of Puerto Peñasco, Sonora between the Gulf of California shoreline and the Pinacate volcanic field, there are several small lacustrine basins that contain trona and associated saline minerals. There has been production in the past from some of the lakes, but only on a very minor scale. The geology is difficult to observe, because the region is covered by Quaternary sand dunes up to 5 m thick. The largest lake, Santa Elena, is about 900 m by 500 m, and contains a 1 m thick accumulation of trona, halite, burkeite and sylvite. The sodium carbonate resources at Santa Elena are about 200,000 tonnes. It is believed, that leaching of the Pinacate volcanic rocks to the east was the source of the brines, that were later deposited as saline minerals in the lakes through biological action (Carbonell and Bustillo, 1978; Armijo, 1987).

The Sonoran Basin and Range Province seems to have a high potential for evaporite minerals. Besides the trona deposit cited above, borate mineralization, mainly in the form of colemanite, has been identified and partially evaluated in the Tubutama-Magdalena de Kino area, about 90 km south of the Sonora-Arizona border. Additionally, a large thenardite deposit with more than 20 million tonnes has been evaluated in the Bacadehuachi area, about 170 km northeast of Hermosillo. This is almost at the boundary between the Sonoran Basin and Range, and the Sierra Madre Occidental Provinces.

## Other minerals

Wollastonite deposits occur north of Hermosillo, in a sequence of Paleozoic calcitic marbles and quartzites, in close proximity to granitic rocks of Cretaceous age. Reserves grading more than 50% wollastonite have been delineated.

## Sierra Madre Oriental and Mesa Central

This province contains Jurassic phosphate deposits hosted in the La Caja Formation, located in the States of Coahuila and Zacatecas. However, because of a high calcium carbonate content, they have not reached commercial production. The ultramafic metamorphosed rocks near Ciudad Victoria, Tamaulipas contain asbestos (chrysotile) deposits, as well as ilmenite within schist and gneiss.

## Fluorspar

The Salitrera mining district contains two fluorspar mines, Las Cuevas and La Consentida, and is located 45 km southeast of the city of San Luis Potosí. The Rio Verde district also has two main mines, El Realito and El Refugio, and is located about 110 km southeast of the city of San Luis Potosí.

In general, the fluorspar deposits are: 300 to 600 m long, 50 to 100 m wide and 95 to 500 m below the surface. They are replacement deposits, hosted mainly in reef

limestones of the early Cretaceous El Doctor Formation and less frequently in a series of caldera-related volcanic rocks and breccias. Proven reserves are over 15 million tonnes with an average grade of 84.5%  $\text{CaF}_2$ .

The emplacement of the deposits was mainly along high-angle normal faults that strike northwest, where the limestones and Tertiary volcanics are in contact. Fluorine inclusion studies have shown that the latest fluorspar emplacement took place at about 80°C.

## Celestite

Celestite deposits in México occur as manto, vein and breccia types. Mantos are commercially the most important, and are located between the cities of Torreón and Saltillo, and also northwest of Torreón.

The host rock for the celestite is a massive limestone of lower Cretaceous age. These manto deposits can be up to about 4 m in thickness and almost 1 km in length. In most areas, there are two mantos separated by three-tenths of a m or more of micritic limestone. However, there can be as many as 10 mantos within a 92 m thick stratigraphic sequence.

The celestite is usually white. Two forms have been recognized: (1) anhedral, equant crystals and (2) elongate, intergrown blades. Associated minerals are calcite, and to a minor extent fluorite and native sulfur.

## Saline minerals

The Laguna del Rey playa lake deposit is located in western Coahuila, about 170 km north of the city of Torreón. This is an area of deeply buried alluvium-covered Sierra Madre Oriental folds. The stratigraphic sequence at Laguna del Rey consists mostly of calcareous rocks of early Cretaceous to Tertiary age.

The subsurface evaporite deposit lies in a synclinal valley, striking almost north-south. It is about 10 km long, approximately 4 km wide and lenticular in cross-section with a maximum thickness of 35 m. The horizon consists of glauberite, with subordinate bloedite, and other minor sodium and magnesium salts, including halite. A small amount of mirabilite is also present, commonly cementing glauberite crystals. Gypsum is most abundant near the bottom of the horizon, and also occurs as thin lenticular beds at higher elevations. A red to green clay bed, 1 to 2 m thick, is present in the horizon. The overburden is only a few m thick, and consists of small gypsum crystals intermixed with silt. The brine, which occupies pore spaces in the evaporite body, on average contains 320 grams/liter of salts, consisting of:

Na	20.3%
Mg	8.5%
Cl	14.8%
$\text{SO}_4$	56.4%



## Trans-Mexico Neovolcanic Belt

Lake Texcoco is located in the northeastern corner of México City. The lake is about 36 sq km in size. Sodium carbonate bearing brine is pumped from two horizons, at 5 and 55 m in depth, which are enclosed within a mostly clay sequence, with minor siltstone and sandstone intercalated. The shallowest horizon, "Capa Dura 1," is continuous for about 7.5 km along strike, and decreases in thickness from 6 m at the north end of the lake, to 0.5 m at the south end. It has an average grade of almost 9% total alkalinity. The underlying horizon, "Capa Dura 2," decreases in thickness from 12 m at the north end, to 7 m at the south end of the lake. It is continuous for approximately 5 km along strike. This horizon has an average grade of 7.8% total alkalinity.

The grade of the brines, although concentrically distributed, have remained fairly constant throughout many years. It has been postulated, that the overlying clay sequence contained salts, and through downward leaching of waters, the sodium carbonate has accumulated in the two horizons, Capa Dura 1 and 2.

## Gulf Coastal Plain and Yucatán Peninsula

There is a series of alkaline rocks located southeast of Ciudad Victoria, Tamaulipas, that extends up to the central part of New Mexico in the United States. In México, these rocks occur in parts of the Gulf Coastal Plain and Sierra Madre Oriental Provinces. The Mexican localities are in: (1) the Sierra de Tamaulipas area, 70 km southeast of Ciudad Victoria (Elias, 1983); (2) the Sierra de San Carlos area, about 60 km north of Ciudad Victoria; (3) the Sierra de Picachos area, 50 km north of Monterrey, Nuevo León and (4) probably the Pico Etereo area, just south of the Big Bend National Park in Texas.

In the Sierra de Picachos area, there is a 7 sq km area of calc-alkaline and alkaline rocks, as well as latitic and aphyric dikes. It was discovered in a preliminary survey, that rare-earth minerals occur within the dikes, which are up to 9 m in thickness, and are continuous for 300 m. The average content is 1.1% rare earths (Elias, 1984).

Geological and geophysical exploration of the salt dome Tancamichapa, at the Isthmus of Tehuantepec, has indicated reserves of 12 million tonnes of sylvite and carnallite, at approximately a 600 m depth. The deposit has not been developed despite the large imports of potassium minerals (Salas, 1989).

## Sierra Madre Del Sur

### Graphite

Significant flake graphite deposits are located in the central portion of the State of Oaxaca, within the Telixtlahuaca municipality, about 30 km northwest of the city of Oaxaca. The regional geology includes the (1) Hielo (Ice) Group from the middle Proterozoic; (2) the Vigalito Supergroup that consists of mafic and ultramafic intrusives, as well as pegmatites from the late Proterozoic; and (3) Triassic red beds and some limestone beds of probable middle Cretaceous age.

Graphite deposits are contained within the Hielo Group rocks, and consist of paragneisses, which range in composition from quartz-feldspathic, through micaceous and graphitic. The deposit itself is within a graphitic gneiss package up to 130 m thick, that strikes NW-SE, and dips between 25 and 50 degrees to the northeast. The graphite content varies from traces up to 6.5%. It is disseminated and oriented parallel to the foliation of the host rock. There are occasional small pockets of graphite. Reserves have been estimated at 3 million tonnes and resources of 5.7 million tonnes have been outlined. Additionally, the graphitic gneiss has been mapped along 15 km, and potential areas are under investigation. According to Enciso de la Vega and Cárdenas (1991) the metasedimentary region that has potential for containing flake graphite covers an area of about 750 sq km. There are more than 30 flake graphite localities in Oaxaca, in what has been called the "Oaxacan graphitic belt" (Enciso de la Vega and Cárdenas, 1991).

Because of the low initial graphite content, the material is blended at the mine site, in order to produce a homogeneous feed for the plant, where flotation raises the grade to 94% carbon.

The metamorphic rocks, in the States of Puebla and Guerrero, are similar to the gneisses in the graphite-bearing region of Telixtlahuaca. They have not yet been investigated.

### Titanium minerals

The best known of the titanium deposits in Oaxaca are those located less than 50 km northeast of the city of Oaxaca, in parts of the Telixtlahuaca, Huitzo and Tenexpan municipalities. Deposits are predominantly ilmenite, with iron, phosphorous and subordinate rutile. Ilmenite occurs disseminated and massively in mantos parallel to the gneissic foliation of the host rock. Disseminated ilmenite deposits may be as much as 20 m thick; the more consolidated mantos, 2 to 6 m thick. They are affected by local tensional and compressional folding, and are horizontally displaced along small faults.

The host rock is a quartz-feldspathic to hornblende gneiss of the Precambrian Oaxaca basal metamorphic complex. Most of the mineralization is in the quartz-feldspathic gneiss, possibly as the result of magnetite replacement in intermediate intrusives, that was subsequently remobilized during regional metamorphism. Another hypothesis proposes, deposition of marine heavy-mineral sands along broadly extensive coastlines, which were subsequently metamorphosed to form the mantos. A very preliminary resource evaluation study indicated a potential of about 8 million tonnes, with an average grade of 8-10%  $\text{TiO}_2$  (Diaz, 1991).

The Ventanilla Beach, in southern Oaxaca, represents a high concentration of heavy minerals in the form of a titanium and zircon deposit. The heavy minerals were transported along the Tonameca river, which ends about six km west of Ventanilla, from where long shore currents transport the sediments toward the east-southeast. The resulting deposit consists of medium-grained, well sorted and submature sand; the heavy minerals are mainly fine and very fine grained. It has been estimated, that in an area of about 160,000 sq m there are 1.8 million tonnes of sand containing about 7%  $\text{TiO}_2$ , 0.03%  $\text{ZrO}_2$  and 41%  $\text{Fe}_2\text{O}_3$ . There is an additional 2.5 sq km area that has not been evaluated (Martin and Osuna, 1982). Similar heavy mineral sands along the Pacific shoreline, between Zihuatanejo, Guerrero, and the state boundaries of Guerrero and Oaxaca, have been briefly studied. This study indicates potential regions as the Cayacal Beach, between Zihuatanejo and Acapulco, and the Ventanilla Beach described above (Martin, 1987).

### Mineral diversity

The Concepción Pápalo asbestos deposit is located north of the city of Oaxaca, within the Cuicatalán municipality. It is included in a Paleozoic metamorphic sequence

made up of quartz-muscovite-chlorite schists, quartzite, phyllites and sporadic metagranites. Serpentine-group chrysotile is the commercial mineral occurring as slip fib, and very sporadically, as cross-fiber veinlets. In addition, talc is widespread in the deposit, and occurs disseminated in the massive asbestos (talc schist) and in laminar form (Ramírez, 1991).

There are ultramafic rocks in the province, and a serpentine deposit has been preliminarily evaluated for talc, in a region not far from the Lazaro Cárdenas steel works in the State of Michoacán (Morales, et al., 1988). Talc exploration and production is in the initial stage. Currently, only small deposits of impure talcs are being exploited. It has been estimated that total production, around 30,000 tonnes a year, comes mainly from the States of Puebla (50%) and Zacatecas (30%) (Rubio, 1989).

In the southern end of México within the State of Chiapas, there has been exploration for bauxite or bauxitic clays. Nine areas within the state were preliminarily evaluated, and the conclusion was that, due to the weathering of Tertiary volcanics, one of the areas contains a potential of about 2 million tonnes of clays, with an average of 36%  $\text{Al}_2\text{O}_3$  (Morales, et al., 1989).

In the State of Michoacán, there are kaolin deposits that have a high pyrometric cone equivalent. The States of Michoacán, Guerrero, Puebla and Oaxaca contain bauxite deposits, that have had some small production in the past. In Oaxaca, near Huitzo, there is potential for vermiculite, feldspar, quartz and rare earths in pegmatites, in addition to rutile in Precambrian schists. Near Huajuapán de León, there is also kaolin. In Chiapas, near the small town of Buenos Aires, there are reports of kaolin, and close to Ocozocauhtla, there is a wollastonite deposit associated with a copper bearing intrusive.

## MARKET FACTORS

### Major Minerals

This section provides an overview of the production, consumption, exports, imports, specifications and other market factors of importance, to the nonmetallics industry in México. As outlined in the introduction, México is a leading producer of a wide range of nonmetallic minerals. Table 3 lists the nine most important which are described in some detail below. Table 4 lists additional selected industrial minerals production.

#### Barite (Barita)

Utilization, as a weighting agent, in drilling mud accounts for around 90% of barite's consumption in México, with Petróleos Mexicanos (PEMEX) being, by far, the largest consumer. Drilling-mud grade barite must conform to specification PEMEX-IMP 1/84, equivalent to API standards, which requires:

- density of 4.23 gm/cm<sup>3</sup>
- maximum 4% retained on 200 mesh screen
- minimum 8.5% retained on a 325 mesh screen
- maximum 300 ppm soluble solids

The volume consumed, largely based on domestic sources, varies according to drilling activity, which, in turn, is dependent upon the price of oil and the state of the economy. Non-drilling uses, largely based on imported high-grade barite, include chemicals, ceramics and fillers. In the chemical industry, barite is converted to barium sulfide (black ash), which is used as the starting material in the production of barium carbonate, barium chloride, barium hydroxide and synthetic barium sulfate (blanc fixe). Barium carbonate, which is used in black and white television glass, is often produced in the same plant as strontium carbonate (see Celestite section). Natural ground barite is used as a filler and extender in paints, paper, rubber, plastics and in friction materials.

Influenced by the changing fortunes of the oil industry through the 1980's, barite production in México has fluctuated from a low of 200,000 tonnes, to near full capacity of over 500,000 tonnes/year. Imports and exports have been equally variable, for example imports totalled 85,600 tonnes in 1991, compared with 36,000 tonnes in 1990, and exports fell from 41,000 tonnes in 1990, to 35,200 tonnes in 1991 (Figure 4).

México's barite production capacity of around 544,000 tonnes/year (equal to that of Morocco and the former USSR) is concentrated around Mazatán, Sonora; Coalcomán

Table 3. México's world ranking in production.

	Production capacity		México as	
	Mexican	World	% world	Rank
Strontium carbonate	95,000	190,000	50%	1
Natural sodium sulfate	650,000	2,500,000	26%	1
Fluorspar	1,284,000	7,700,00	17%	3
Barite	544,000	8,174,000	7%	4
Graphite	45,000	700,000	6%	5
Sulfur	2,775,000	68,881,000	4%	7
Feldspar	117,000	4,437,00	3%	7
Salt	7,000,000	225,000,000	3%	8
Gypsum	7,000,000	106,000,000	7%	11

#### Notes:

1. On January 1, 1993, the government of México changed the currency basis by deleting the 1,000's, i. e., the last three zeroes on the currency and in any transaction were eliminated:

Old peso \$1,000.00 = New peso N\$1.00

The exchange rate used in this paper to convert between U. S. dollars and pesos is:

Old peso \$1,000.00 or N\$1.00 = US\$0.33 or US\$1.00 = N\$3.00.

Because the conversion rates have changed over the years, and will continue to change, any dollar amounts shown in this study should be considered order-of-magnitude only.

2. N.A. means Not Available.

3. All figures are for 1991, the latest year available.

4. Tonne and dollar (originally in pesos) amounts are from statistics compiled by the Consejo de Recursos Minerales division of the Secretaría de Energía, Minas e Industria Paraestatal. Producers and mine locations are partially derived from the publications of the US Bureau of Mines and from other sources shown under "Bibliography."

5. ALL TONNAGE FIGURES ARE IN METRIC TONS (TONNES) UNLESS OTHERWISE SPECIFIED.



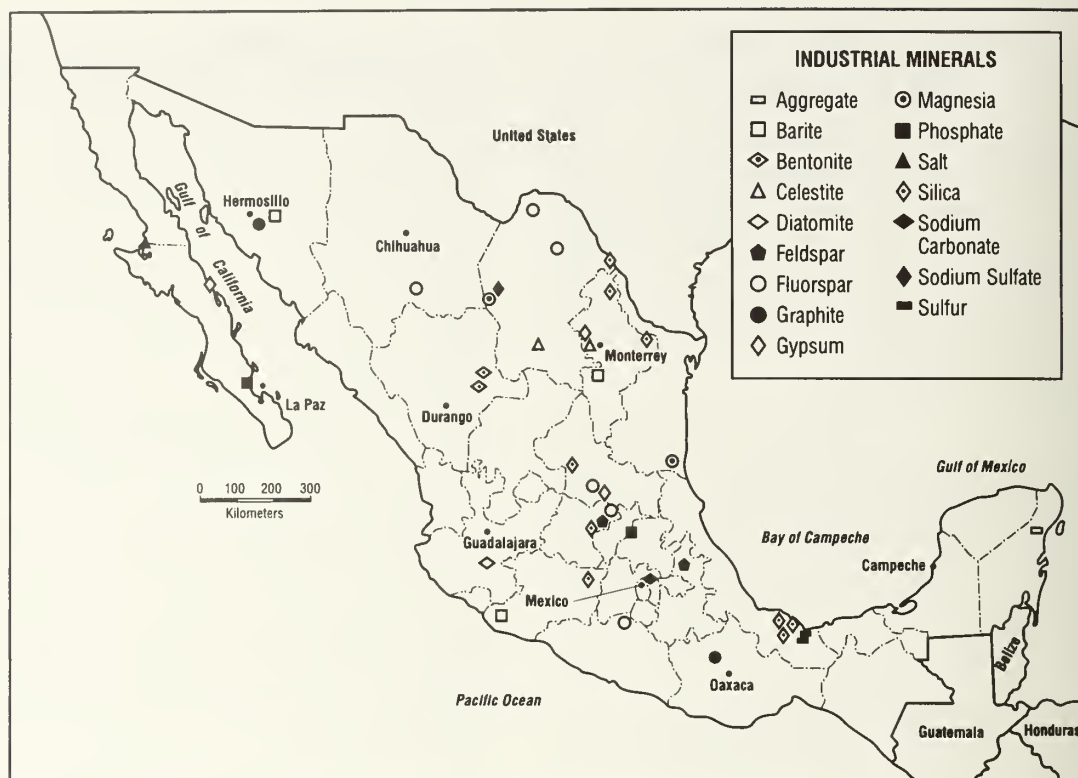


Figure 3. Selected industrial mineral mining locations.

Table 4. Production of selected industrial minerals in México (tonnes).

	1987	1988	1989	1990	1991
Asbestos	-	-	-	-	-
Barite	401,336	534,954	324,739	305,716	203,974
Bentonite	129,596	163,916	123,927	144,895	145,347
Calcium carbonate	486,740	436,183	444,000	445,415	457,925
Celestite	47,739	51,626	67,658	64,254	62,280
Clays*	178,347	3,593,060	3,828,156	3,829,507	3,922,208
Diatomite	34,708	36,524	44,820	51,084	45,966
Dolomite	411,601	395,671	469,564	482,168	470,665
Feldspar	106,490	83,170	121,978	163,011	151,678
Fluorspar	723,594	756,096	779,357	633,814	370,297
Fuller's Earth	43,112	37,226	24,603	29,863	41,075
Graphite	38,461	49,607	40,246	24,918	37,298
Gravel (m <sup>3</sup> )	29,338,848	35,657,424	36,801,072	37,737,216	39,746,950
Gypsum	4,575,416	4,779,827	5,350,391	5,423,804	4,774,130
Kaolin	151,104	162,415	141,519	156,140	167,238
Limestone	23,735,368	24,740,903	26,127,113	27,405,529	29,477,115
Magnesia	7,351	5,384	4,229	579	-
Manganese	146,407	168,573	149,875	138,850	78,450
Marble	261,000	468,000	524,160	681,408	749,548
Mica	3,419	6,228	4,510	5,863	5,587
Perlite	39,428	39,169	37,354	42,439	48,860
Phosphate	688,973	835,093	655,477	623,481	596,392
Salt	6,393,042	6,788,359	6,942,165	7,135,121	7,532,421
Sand (m <sup>3</sup> )	36,866,039	42,259,589	42,773,361	44,699,839	44,011,618
Silica <sup>+</sup>	992,171	1,001,823	1,216,443	1,298,292	1,366,356
Sodium sulfate	486,245	502,448	603,551	650,000	650,000
Sulfur	2,303,775	2,138,240	2,086,333	2,122,482	1,814,555
Talc	17,469	13,645	13,534	13,477	11,883'
Vermiculite	161	218	300	132	117
Wollastonite	10,993	10,506	10,618	11,442	13,877

\* comprises ceramic and refractory clays

+ includes grades used for glass, quartz, and silicon.

Source: Dirección General de Mines, S.E.M.I.P. e Investigación directa.

## BARITE (BARITA)

Capacity: 544,000 tonnes  
 Production: 203,975 tonnes  
 US\$14,840,000  
 Exports: 35,197 tonnes  
 US\$ 1,869,000  
 Imports: 85,601 tonnes  
 US\$4,257,000

Comments: World's fourth largest producer.  
 Drilling activity in México,  
 the United States, and overseas  
 greatly influences demand.

### Major Producers

Barita de Sonora, S.A.  
 Baramín, S.A.  
 Barita de Santa Rosa, S.A.  
 Bentonita de México S.A.  
 Barita de Apatzingán, S.A.  
 Minerales y Arcillas S.A.  
 Negociación Minera Eulalio Gutiérrez, S.A.  
 Minera la Capela S.A.

## Mexico

### Production of bentonite & barite



### Mine Locations

Mazatán, Sonora  
 Galeana, Nuevo León  
 Múzquiz, Coahuila  
 Linares, Nuevo León  
 Tecalitlan, Jalisco  
 Galeana, Nuevo León  
 Saltillo & Múzquiz, Coahuila & Linares, Nuevo León  
 Coalcomán, Michoacán

Figure 4. Barite production



Figure 5. Barite mining operations.

and Apatzingán in Michoacán; Galeana region of Nuevo León; near Julimes and Allende in Chihuahua; Tecalitlán, Jalisco and Múzquiz, Coahuila. Minerales y Arcillas S.A. at Galeana, Nuevo León, sells its barite in bulk to PEMEX, and also exports significant quantities to its US subsidiary, Milwhite Company Inc. in Houston, Texas. Dresser-Halliburton, the major US drilling service company, has a 49% shareholding in three Mexican barite producers: (1) Baramin S.A., with a mine at Galeana, and plants at Linares and Monterrey, Nuevo León; (2) Barita de Santa Rosa, S.A., with a mine and plant at Múzquiz, Coahuila and (3) Bentonita de México S.A., with facilities at Linares, Nuevo León. Barita de Sonora S.A. appears to have ceased or, at least, drastically reduced production from its 265,000 tonnes/year operation at Mazatán, Sonora. This is due to high transportation costs to the southern Gulf of México oilfields. The Barita de Apatzingán, S.A. operation at Tecalitlán, Jalisco, has apparently depleted its reserves (Figure 5).

### Calcium Carbonate

#### (Carbonato De Calcio)

Describing the production of the vast quantities of limestone used to make cement, lime, aglime and construction aggregate in México, is beyond the scope of this paper. However, it should be remembered that México is a major cement manufacturer, with more than 30 plants and an installed capacity of approximately 35 million tonnes/year, as well as exports approaching 20 million tonnes/year (Figure 6). The largest producer is the Grupo Cementos Mexicanos S.A., with its six subsidiary companies, accounting for over 70% of the country's capacity.

Ground calcium carbonate is produced in México for use as a filler in paper, paints, plastics, adhesives, dry-wall

joint cement, putty and sealants, etc. Depending on the end use, this calcium carbonate needs to be chemically pure and white, with a specific particle size, particle shape and particle-size distribution. The price varies enormously, depending on the specifications (see graph). Nominally, a limestone should have a brightness of at least 85 to be considered a filler-grade "calcium carbonate".

#### Celestite (Celestita)

Strontium is mined as celestite,  $\text{SrSO}_4$ , which is then converted to the carbonate,  $\text{SrCO}_3$ , for commercial use. In the black ash process, the most commonly used process, celestite ore is reduced by coal or coke, to form the water-soluble sulfide, which is then filtered to eliminate solid impurities. The addition of either soda ash or carbon dioxide gas, converts the sulfide to carbonate, which precipitates out a high-quality chemical-grade strontium carbonate, with a minimum  $\text{SrCO}_3$  content of 98%. Strontium nitrate, the second most common strontium chemical sold, is often produced at the same plant.

The major commercial use of strontium is as an ingredient in color TV tube glass, since it absorbs the gamma radiation resulting from the high cathode potentials, used to produce a bright picture. Strontium is also used to improve the physical characteristics of other types of glass, particularly optical glass, and certain ceramics, like frits and glazes. Strontium carbonate and iron oxide are combined to produce ferrites, which are utilized in DC motors, loudspeakers and door magnets, etc. Other uses of strontium are in the production of pyrotechnics, specialized soaps, lubricants, paint, and in certain metallurgical processes, such as the preparation of high-quality electrolytic zinc.

### CALCIUM CARBONATE (CARBONATO DE CALCIO)

Production: 457,925 tonnes  
US\$15,412,000  
Exports: Nominal  
Imports: N.A. tonnes  
US\$4,105,000

Major Producers and Mine Locations:  
34 companies

Comments: Production of calcium carbonate doubled in the mid-1980's (Figure 6), partly due to increased industrialization but mainly because of the switch to alkaline sizing in the paper-making process that permits the use of calcium carbonate in addition to kaolin.

### Mexico

#### Production of calcium carbonate

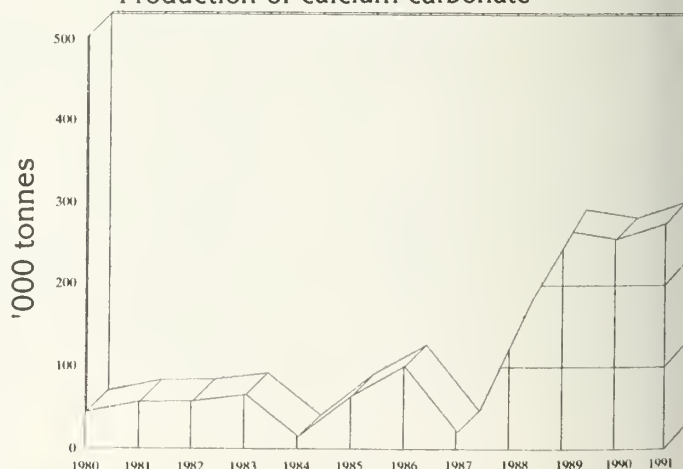


Figure 6. Calcium carbonate production.



## CELESTITE (CELESTITA)

Production: 62,180 tonnes

US\$2,250,000

Exports: 40,000 tonnes (estimated)

US\$8,080,000

Imports: Nominal

Comments: World's largest producer of celestite ore and strontium carbonate. Most of the carbonate is exported to the United States, Japan, Korea, and Europe for use in TV tube manufacturing.

### Major Producers

Cía. Minera la Valenciana, S.A.

Salas y Oxidos, S.A.

Química Dinámica S.A. de C.V.

Minera la Roja S.A.

## Mexico

### Production of celestite



### Mine Locations

San Agustín and Marte, Coahuila

San Pedro, Coahuila

Coahuila

Madero, Coahuila

Figure 7. Celestite production.



Figure 8. Principal producers of celestite and processing plants for strontium carbonate.

México has the capacity to produce about 140,000 tonnes/year of celestite ore, although captive consumption to produce strontium carbonate, means that only a fraction of this reaches the open market. The main deposits are in the state of Coahuila, in particular at San Agustín and Matamoros, between Torreón and Saltillo, and at Bermejillo, to the northwest of Torreón. Deposits are also located at Escalon, to the northwest of Torreón (Figure 7).

As mentioned above, much of the celestite ore mined in México is now converted to strontium carbonate. In fact, México's four plants have the capacity to produce approximately 95,000 tonnes of strontium carbonate, which is equivalent to half the world's production capacity (Figure 8). In addition, the other large producers, Korea (40,000 tonnes/year), Japan (31,000 tonnes/year), the United States (22,000 tonnes/year) and Germany (15,000 tonnes/year), have to depend on imported celestite ore from México, Turkey or Spain.

Table 5. Strontium carbonate producers in México

Producer/Plant location	Rated capacity (tonnes)
Compañía Minera la Valenciana S.A. de C.V. Torreón, Coahuila	50,000
Sales y Oxidos S.A. de C.V. Villa de Garcia, Nuevo León	15,000
Chemical Products Corp. Reynosa, Tamaulipas	22,000
Química Dinámica S.A. de C.V.* Monterrey, Nuevo León	8,000
Total	95,000

\* announced plans to build a 30,000 tonnes/year plant

Compañía Minera la Valenciana S.A. de C.V. operates the San Agustín underground mine located between Torreón and Saltillo in Coahuila. The reserves are estimated at 750,000 tonnes, averaging 92%  $\text{SrSO}_4$  (minimum 90%  $\text{SrSO}_4$  guaranteed), 0.80%  $\text{BaSO}_4$ , and 0.50%  $\text{SiO}_2$ , with much of the remainder made up of calcium sulfate. The ore is upgraded to 94%  $\text{SrSO}_4$  at a beneficiation plant at Marte, Coahuila, which in turn feeds the company's strontium carbonate plant at Torreón (the equipment was purchased from FMC Corp. when that company closed its US plant in 1984). The plant has the capacity to produce 50,000 tonnes/year of strontium carbonate, which is equivalent to 20% of world production. The product quality is summarized in Table 6.

Table 6. Typical chemical analysis of strontium carbonate

$\text{SrCO}_3$	98.5%	$\text{BaCO}_3$	1.0%
$\text{CaO}+\text{MgO}$	0.05%	$\text{Na}_2\text{CO}_3$	0.20%
$\text{Fe}_2\text{O}_3$	0.0018%	S as $\text{SO}_3$	0.18%
$\text{SiO}_2$	0.20	Moisture	0.15%

Source: Compañía Minera la Valenciana S.A. de C.V.

Sales y Oxidos S.A. de C.V., owned 86% by Solvay S.A. of Belgium, produces celestite from an underground mine at San Pedro, Coahuila. The 93-94%  $\text{SrSO}_4$  ore, with 0.4%  $\text{BaSO}_4$ , is hand sorted and crushed at the mine site, prior to conversion to its 15,000 tonnes/year strontium carbonate plant at the plant at Villa de Garcia, near Monterrey, Nuevo León. The plant, which produces barium carbonate, as well as the minimum 98.5%  $\text{SrCO}_3$  product, was opened in 1990. Química Dinámica S.A. de C.V. uses captive and purchased celestite ore to feed its 8,000 tonnes/year strontium carbonate and nitrate plant in Monterrey. There are plans for Química Dinámica to join with a Japanese company to form Cistron Mexicana S.A. de C.V., and build a 30,000 tonnes/year strontium carbonate plant.

Chemical Products Corp., which operates a strontium carbonate and nitrate plant in Cartersville, Georgia, opened a 22,000 tonnes/year  $\text{SrCO}_3$  plant at Reynosa in Tamaulipas in 1991. The plant, located close to the border with the United States, is fed by purchased celestite ore.

In 1990, Minera La Roja S.A. began mining celestite at the La Ilusion Mine in southern Coahuila. The mine has an annual capacity of 42,000 tonnes and yields a minimum 95%  $\text{SrSO}_4$  concentrate through flotation at the company Madero plant, some 60 km south of the mine. The company exports the concentrate, mainly via rail, to the port of Brownsville, Texas.

Clays (Arcillas)

Bentonite (Bentonita)

Sodium bentonite swells when immersed in water, a property used in several industries. Bentonite is second only to barite as the largest tonnage ingredient in oilwell drilling muds. It is the main binder used for foundry sands and in iron-ore pelletization. Bentonite is also a practical and efficient sealant in the lining of ponds and various waste dumps. Minor uses include being a thickener for products, such as toothpaste and non-drip paints. Sodium bentonite may be produced synthetically from calcium bentonite, the non-swelling variety, by the addition of sodium chemical, usually soda ash. A rather unusual form of bentonite is white bentonite, which is utilized for emission stabilization in cosmetics, toiletries and household products. Other uses of white bentonite are as a plasticizer in electrical ceramics, as a softening agent in detergents and as a gelling agent in household products. Activated bentonite, manufactured through the reaction of inorganic acids with bentonite, has excellent absorbent and catalytic properties.

Production of bentonite in México declined from an average of 250,000 tonnes/year in the first half of the 1980's, to the current level of less than 150,000 tonnes/year (Figure 9). The main producer is Química Sumex S.A. de C.V., a Mexicanized subsidiary of Süd Chemie AG of Germany, which mines calcium bentonite in Panot,

## BENTONITE (BENTONITA)

Production:	145,347 tonnes US\$5,458,000
Exports:	N.A. tonnes US\$ 298,400
Imports:	N.A. tonnes US\$ 1,716,300

**Comments:** *Bentonite production is tied to drilling activity both in and outside México. México has been a major world producer, especially when the Hughes Rig Count is high.*

### Major Producers

Química Sumex S.A.

Arcillas Industriales  
de Durango, S.A.

Técnica Mineral, S.A.  
Bentonita de México S.A.

### Mine Locations

Panotla, Tlaxcala (Ca-bentonite)  
Durango, Durango (Na-bentonite)

Cuencamé, Durango (mine) and  
Gómez Palacio, Durango (plant).  
Tlaquepaque, Jalisco (plant)  
Linares, Nuevo León

Figure 9. Bentonite production.

Tlaxcala, and sodium bentonite in Durango, Durango, through its subsidiaries Tonsil Mexicana S.A. de C.V. and Minera Sumex S.A. de C.V. The annual production of around 10,000 tonnes of sodium bentonite is used for the foundry and detergent industries, as well as for pencils and cosmetics. The calcium bentonite is used for the decolorization of oils and fats. Química Sumex's plant in Puebla is the sole producer of acid-activated bentonite in México.

Arcillas Industriales de Durango S.A. de C.V. operates a 140,000 tonnes/year mine at Cuencamé, Durango, which is sodium-exchanged at the plant at Gomez Palacio, also in Durango. Bentonita de México S.A., 49% owned by Dresser-Halliburton, has a 40,000 tonnes/year sodium bentonite

operation at Linares, Nuevo León, but production has been suspended. Técnica Mineral S.A.'s operation at Tlaquepaque, Jalisco, produces around 3,000 tonnes/year.

### Kaolinite (Caolinita)

The most important commercial varieties of kaolinite are kaolin, ball clay and refractory clay. The main commercial outlet for kaolin is as a filler (filler-grade) or coating agent (coating-grade) in the production of various grades of paper. Good quality kaolin is also used as a filler in paints, plastics and rubber, with lower qualities used in adhesives, sealants, putty and the like. Specialty grades of kaolin are used in a range of products that includes (1) cosmetics and catalysts; (2) inks; (3) insecticides; (4) food

## KAOLINITE (CAOLINITA)

### Kaolin

Production:	157,238 tonnes US\$4,518,000
Exports:	Nominal
Imports:	N.A. tonnes US\$17,434,000

**Comments:** Kaolinitic clays are widely produced in México but high-grade kaolin, such as that from Georgia, Australia, and Brazil, has not yet been found. The large dollar volume of imported clays indicates that exploration for the various types of clays could be rewarding, especially when coupled with increased domestic usage.

### Major Producers

Técnica Mineral, S.A.  
Refractarios HW-Flir S.A.  
General de Minerales, S.A.  
Minerales Industriales, S.A.  
Química Magma S.A. de C.V.

### Ceramic and Refractory clays

Production:	3,922,208 tonnes US\$21,414,000
Exports:	Nominal
Imports:	N.A. tonnes US\$13,767,000

### Office Locations

Guadalajara, Jalisco  
Monterrey, Nuevo León  
Monterrey, Nuevo León  
Puebla, Puebla  
México, D. F.

Figure 10. Kaolinite production.



additives and (5) filter aids. In all these uses, there is stiff competition from alternatives, such as calcium carbonate, talc and ground mica. The choice is partly technical suitability, partly cost-effectiveness and partly local supply.

Kaolin is used as a prime ingredient in the ceramics industry for everything from sanitaryware to bone china, and from floor and wall tiles to electrical porcelain. It is often combined with ball clay, a fine-grained mixture of 70% disordered kaolinite plus illite, quartz, montmorillonite, chlorite and small amounts of carbonaceous material. Ball clay is highly regarded in the ceramics industry, because of its high plasticity, good dry strength and long vitrification range. In addition, the carbonaceous material burns off on firing, producing a white or near-white product. Ball clays are also used in refractories, as anti-caking agents in animal feedstuffs, and as fillers in rubber and plastics.

Refractory clay, also known as fire clay, does not burn white, and can stand temperatures above 2,732°F (1,500°C). Since refractory clays have a declining market share, due to competition from magnesite, bauxite and the like, they are being used increasingly in non-refractory products, such as buff facing brick, vitrified clay pipe and ceramic stoneware. The U. S. Bureau of Mines states that a list of "Non-Metallic Mining Industry of México" contains 108

companies in 16 states that produce kaolinitic clays or common clays, with the following being the major states: Hidalgo, México, Nuevo León, Puebla and Michoacán (Figure 10). However, there is a need for increased production of high-quality kaolin, which is currently imported from the United States.

### Feldspar (Feldespatos)

More than 60% of the feldspar produced is used in glass manufacture, and an additional 35% in ceramics. In the glass and ceramic batch, feldspar is principally a source of alumina and alkalis, which act as a flux and stabilizer. Na-spar is generally more popular in glass, and K-spar in ceramics. Fine-ground grades of feldspar may be used as a filler in plastics, paint and rubber, and as a mild abrasive.

Feldspar is the most abundant mineral in the earth's crust, and commercial production is recorded in nearly 50 countries. However, the top ten producers, which include México, account for well over 90% of the 5 million tonnes plus, produced each year worldwide. A large proportion of the Mexican feldspar production (Figure 11) is controlled by major consumers; for example, in the Guanajuato district, Materias Primas Minerales de San José S.A. de C.V., a subsidiary of Vitro Química, Fibras y Minería operates a 70,000 tonnes/year potassium feldspar mine at San José Iturbide. This is based on a Miocene crystalline

### FELDSPAR (FELDESPATO)

Production: 151,578 tonnes  
US\$8,149,000

Exports: N.A.  
US\$1,607,000

Imports: Nominal

Comments: The largest producers are subsidiaries of Vitro Química, Fibras y Minería and the Lamosa Group, the largest glass and ceramics manufacturers in México, and consequently consumption is captive. Some is exported, principally to the United States.

#### Major Producers

Materias Primas Minerales de Ahuazotepec S.A. de C.V.

Materias Primas Minerales de San José S.A. de C.V.

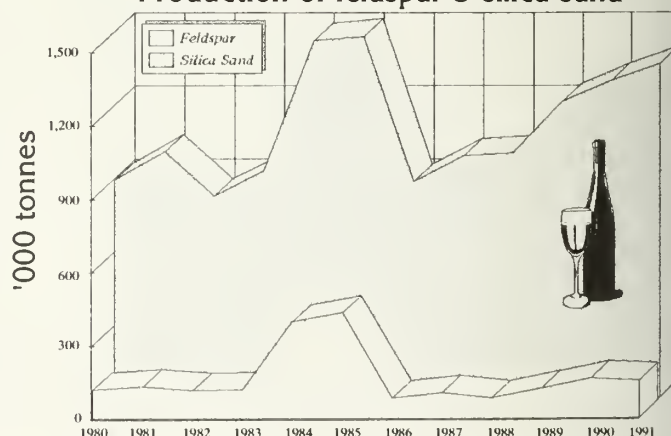
General de Minerales, S.A.

Técnica Mineral, S.A.

Minerales La Cruz del Sur, S.A.

### Mexico

#### Production of feldspar & silica sand



#### Mine Locations

Ahuazotepec, Puebla

San José Iturbide, Guanajuato

Ahuazotepec, Puebla

Guadalajara, Jalisco

San Pedro Cholula, Puebla

Figure 11. Feldspar production



Figure 12. Flourspar mining districts and selected flourspar mine locations.

## FLUORSPAR (FLUORITA)

**Production:** 370,297 tonnes

US\$93,201,000

**Exports:** 255,200 tonnes

US\$21,395,000

**Imports:** Nominal

**Comments:** World's third largest producer. Most exports are to the United States. Fluorspar consumption has been adversely affected by decreased demand in metallurgical usage (steel and aluminum) and the phasing out of fluorocarbon chemicals.

### Major Producers

Cía. Minera Las Cuevas, S.A.

Flourita de México, S.A.

Asociación Nacional de Pequeños y Medianos

Productores de Fluorita, A.C.

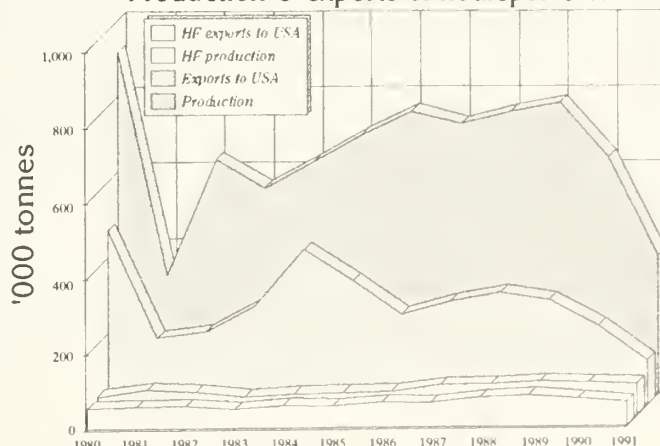
Minerales y Productos Metalúrgicos S.A.

Minera Múzquiz, S.A.

Cía. Minera la Valenciana, S.A.

## Mexico

### Production & exports of flourspar & HF



### Mine Locations

Zaragoza, San Luis Potosí and Taxco de Alarcón, Guerrero  
Múzquiz, Coahuila (plant)

Múzquiz, Coahuila (plant)

Indé Durango (mine), Gómez Palacio, Durango (plant)

Múzquiz, Coahuila (plant)

General Cepeda, Coahuila

Figure 13. Flourspar production and exports of flourspar and hydrogen fluoride.

tuff containing 40-45% quartz and potassium feldspar. A sister company, Materias Primas Minerales de Ahuazotepec S.A. de C.V., also produces feldspar at Ahuazotepec, Puebla. Much of the production, from both operations, is used for the parent's glass production, although some is exported, particularly to the United States. General de Minerales S.A. is a subsidiary of the Lamosa Group, which is a large ceramic producer, and therefore, consumer of feldspar.

## Fluorspar (Fluorita)

### Production and grades

Commercial fluorspar is generally divided into three main grades: metallurgical, acid and ceramic. Over half of México's fluorspar production capacity is metallurgical and submetallurgical-grade (metspar). Metallurgical-grade, generally contains a minimum of 60 "effective%" fluor-spar, less than 0.3% sulfide and less than 0.50% lead. The effective% is calculated by multiplying the silica percentage in the chemical analysis by 2.5, and subtracting the result from the calcium-fluoride percentage. For example, an 85%  $\text{CaF}_2$  concentrate with a 6% silica content is a 70% effective grade. Submetallurgical-grade, generally contains a minimum  $\text{CaF}_2$  content of 80% with a maximum of 15% silica. Metspar is used in steelmaking, as a fluxing agent.

Another 40% plus of Mexican production capacity is acid-grade fluorspar (acidspar), which contains a minimum of 97% calcium fluoride, less than 1.50% silica and 0.03 to 0.10% sulfur as sulfide and/or free sulfur. Other limitations may include content of calcium carbonate or moisture, as well as grain size. This fluorspar is a feedstock for the manufacture of hydrogen fluoride, HF, which is the starting point in the production of a variety of fluoride chemicals, fluorine, fluorocarbons and synthetic cryolite. It is also used directly in steel pickling, enamel stripping, glass etching and polishing, electroplating, and as a catalyst. As described below, México is a major producer of HF, based on its captive fluorspar.

Less than 2% of the fluorspar produced in México is classified as ceramic-grade, that is containing 95-96% calcium fluoride (No.1 grade), or 80% to over 90% calcium fluoride (No.2 grade). These grades are used mainly to make various glasses and enamels.

### Production and producers

México is losing the battle with Mongolia to be the world's second largest fluorspar producer, after China. In fact, production in México peaked at over 1.1 million tonnes in 1974, and has since declined to only 352,000 tonnes in 1991. There have been wholesale closures in recent years, including (1) Minera San Francisco del Oro, S.A. in San Francisco del Oro, Chihuahua; (2) Zinc de México S.A. at Hidalgo del Parral, Chihuahua and (3) Fluorita de Río Verde, S.A. at San Luis de La Paz, Guanajuato.

These producers, plus one or two smaller operators, represent about 50% of the country's production capacity. The surviving fluorspar producers in México are listed in Table 7.

México's emasculated fluorspar industry is largely concentrated in the northern States of San Luis Potosí, Chihuahua, Coahuila, and Durango (Figure 12). High-grade fluorite in the Zaragoza-Río Verde district is the source of much of México's production, including the country's largest individual producer, Compañía Minera Las Cuevas S.A.'s Las Cuevas mine, near Zaragoza, San Luis Potosí, which has a capacity of about 500,000 tonnes/year of acidspar, metspar and ceramic grade fluorspar. However, recent production levels have utilized less than 305,000 tonnes of this capacity. The arsenic level of the ore is high at 260-290 ppm, although this can be reduced, particularly when used to produce 12,000 tonnes/year of HF at the Ciudad Juárez plant of its subsidiary, Fluorex S.A. de C.V. Compañía Minera Las Cuevas S.A., which is 40.6% owned by Noranda Inc., also operates the La Azul Mine, Taxco de Alarcón, Guerrero, which has a capacity of 200,000 tonnes/year.

With the closure of San Francisco del Oro and Zinc de México S.A., the main producer in the Parral district of Chihuahua State is Asociación Nacional de Pequeños Medianos Productores de Fluorita, A.C. (108,000 tonnes/year of metspar and sub-metspar at Múzquiz). In Coahuila State near the US border, several companies work fluorite mines and lead/zinc mine dumps. These include: (1) Fluorita de México S.A. which is 49% owned by AIMCOI (120,000 tonnes/year near Múzquiz); (2) La Domincia S.A. de C.V., which is 13% owned by Du Pont (90,000 tonnes/year of acidspar at Pico Etéreo) and (3) Minerales y Productos Metalúrgicos S.A. (35,000 tonnes/year at

Table 7. Fluorspar production in México (tonnes).

Grade	1987	1988	1989	1990	1991
Acid	409,846	338,000	359,000	268,000	150,000
Ceramic	12,015	27,000	27,000	11,000	5,000
Metallurgical	306,633	253,000	225,000	192,000	107,000
Sub-metallurgical	95,398	138,000	168,000	163,000	90,000
<b>Total</b>	<b>823,892</b>	<b>756,000</b>	<b>779,000</b>	<b>634,000</b>	<b>352,000</b>



Correón). Much of the fluorite in the El Tule district is in the form of discontinuous mantos, which are difficult to mine on a large scale. The Paila-San Marcos district contains veins up to about 11 m wide, as well as manto deposits, and in the Encantada-Buenavista district, mantos are as much as 6 m wide. In the Pico Etéreo district, some orebodies are chimney-shaped, and others are elongate parallel to a limestone-dike contact.

The principal reason for this sharp decrease in demand, is the lower consumption of fluorspar per tonne of steel or aluminum produced, due to improved technology and efficient recycling. For example, the average amount of new fluorine used per tonne of aluminum produced was 32 kg (70 lbs) in the late 1960's, 25 kg (55 lbs) in the late 1970's, 23 kg (50 lbs) in the mid 1980's, and less than 20 kg (45 lbs) today. Consumption of fluorspar per tonne of steel produced has fallen from a worldwide average of more than 4 kg in 1975, to less than 3 kg today. More important, consumption in México's main markets is particularly low, 1.24 kg in North America, and 2.16 kg in South America. Other factors depressing fluorspar sales include the proposed phaseout of CFCs, the effects of the economic recession and competition from other exporters, especially China and South Africa (Figure 13)

### HF production

Four companies in México produce over 90,000 tonnes/year of HF (Table 8). Some degree of vertical integration

occurs in that Fluorex S.A. de C.V. is owned by Compañía Minera Las Cuevas S.A., and Química Fluor S.A. de C.V. is owned by Du Pont. Based on the assumption that 2.2 tonnes of acidspar is required to produce 1 tonne of HF, this industry accounts for almost 200,000 tonnes of acidspar.

More than 60% of the fluorspar and hydrofluoric acid produced in México is exported, mainly to the United States. This "one-way México-United States" trade peaked at 420,000 tonnes of all grades of fluorspar in 1984, since then it has gradually declined to the 1991 figure of 120,000 tonnes (Table 9). The availability of competitively priced imported fluorspar from México has gradually eroded fluorspar production in the United States. Today, Ozark Mahoning Company, itself part of Atochem North America, Inc., the North American arm of Société Nationale Elf Aquitaine of France, is the country's sole fluorspar producer. The virtual elimination of a US fluorspar industry prompted the Government to suspend the 13.5% US import duty on metspar in 1990. This has boosted México's competitive position, since US duty is calculated on an F.O.B. value, and therefore the duty saving on the Mexican product is greater than the freight-burdened Chinese and South African material.

México accounts for 70% to 80% of US imports of hydrofluoric acid, that is approximately 65,000 to 75,000 tonnes/year, valued at about \$1,000/tonne.

Table 8. Hydrofluoric acid producers in México.

Producer	Location	Capacity Tonnes
Química Fluor S.A.	Matamoros, Tamaulipas	65,000
Fluorex S.A.	Ciudad Juárez, Chihuahua	12,000
Industrias Químicas de México S.A.	San Luis Potosí, S.L.P.	10,000
Quimobásicos S.A.	Monterrey, Nuevo León	5,000
<b>Total</b>		<b>92,000</b>

Table 9. Production and exports of fluorspar & HF in México ('000 tonnes).

	Fluorspar production	Fluorspar exports to the USA	HF production	HF exports to the USA
1980	916	471	59	55
1981	925	187	75	57
1982	631	202	70	59
1983	556	271	56	51
1984	627	419	64	60
1985	697	336	66	57
1986	757	246	69	66
1987	724	280	84	65
1988	756	303	86	79
1989	779	283	92	83
1990	633	214	90	75
1991	370	120	85	64

## GRAPHITE (GRAFITO)

Amorphous graphite, which is actually microcrystalline rather than amorphous, is used in the manufacture of carbon brushes by the heat-treatment with a binder, such as coal-tar pitch or synthetic resin. Amorphous graphite is also used in recarburizing steel, and as a starting point in the manufacture of electrodes. In contrast, the more expensive flake graphite is consumed in the manufacture of crucibles, used in the foundry for handling molten steel and other metals. It is also used extensively in magnesite-carbon (mag-carbon) refractory brick, which is particularly suitable for use in the harsh environments associated with water-cooled electric-arc furnaces and BOF furnaces. Flake graphite is used as a lubricant.

México is an important producer of amorphous graphite (35,000 to 40,000 tonnes/year) and a modest supplier of flake graphite (2,000 to 4,000 tonnes/year). Figure 14 provides a history of recent production. In both cases, at least 50% of the production is exported, mainly to the United States. There is considerable US influence in the Mexican graphite industry — Asbury Carbons Inc. owns 25% of Grafitos Mexicanos S.A., 49% of Grafitera de Sonora S.A. de C.V., and 49% of Grafitos Industrializados Mexicanos S.A. de C.V. (Grafimex) while Superior Graphite Co. owns 49% of Grafito Superior S.A.

Grafitos Mexicanos S.A. is the largest producer with an output of some 30,000 tonnes/year from various mines, including the Lourdes mine which is based on three veins of graphite, one of which (the Lourdes Vein) contains ore with over 85% carbon. Grafitera de Sonora S.A. de C.V. operates the San Francisco Mine some 90 km northeast of the port of Guaymas. Grafito Superior S.A. operates underground mines near Hermosillo, Sonora with the capacity to produce 15,000 tonnes/year of crude ore, which is processed at a plant at Torres. This plant, which produces a variety of grades ranging from 75 to 85% C, is due to be expanded from 5,000 to 10,000 tonnes/year in late 1993. A smaller producer with an output of about 8,000 tonnes/year of crude ore, is Explotadora Sonorense de Grafito S.R.L. with underground mines at Tonichi and Las Trincheras.

Crystalline graphite is produced from a surface mine and plant at Telixtlahuaca in the State of Oaxaca, southeast of México City by Grafito de México S.A. de C.V. Grafito de México is an example of a mine that was owned and developed by the government's Fideicomiso de Fomento Minero, and privatized in 1989 by its sale to Minerales Mexicanos No-Metalicos, S.A. This operation, which recovers 2,000 tonnes/year of flake graphite from 50,000 tonnes of ore, was acquired in 1992 by Carbón y Grafito. Four grades of graphite are produced: A (+48 mesh), B (-48 mesh), blend AB and O (-325 mesh). There are plans to upgrade the graphite to a 99.6% carbon product.

## GYPSUM (YESO)

Gypsum is a common, low-priced mineral that is produced in more than 80 countries worldwide. North America produces approximately 30% of the 100 million tonnes/year produced worldwide, with the United States (16 million tonnes/year), Canada (9 million tonnes/year) and México (4.5 to 7 million tonnes/year) being the one, two, and three producers in the Western Hemisphere. The bulk of the gypsum mined is used in the production of paper-covered gypsum board, commonly known as wall-board or sheetrock. Other uses range from the manufacture of plaster, a cement additive to retard the setting time, a soil enhancer, a glass additive, to a filler in pharmaceuticals.

Since transportation costs are so critical for competitiveness, the gypsum/wallboard industry tends to be vertically integrated. For example in the United States producers like USG Inc. (15 mines and 24 plants), National Gypsum (8 and 18), Domtar (8 and 12), Georgia-Pacific Corp. (7 and 10), and Celotex Corp. (3 and 4) have established wallboard plants adjacent to the market and/or a gypsum source. Some of these companies have operations outside the United States, most notably in Canada and to a lesser extent in México. USG Inc. has a 49% stake in Yeso Mexicano S.A., which operates a 280,000 tonnes/year mine at La Borreguita, San Luis Potosí. Other producers include: (1) Yesera Monterrey, S.A. at Mina Nuevo León (150,000 tonnes/year capacity); (2) Yeso El Tigre, S.A. at Lagunillas de Rayón, Puebla (80,000 tonnes/year) and (3) Yesera Nazas S.A. at Matamoros, Coahuila and Gómez Palacio, Durango (60,000 tonnes/year). These companies are all 100% Mexican owned.

However, the largest and most spectacular gypsum producer in México is Compañía Occidental Mexicana S.A. owned 49% by Domtar Ltd. of Canada (Figure 15). This operation on San Marcos Island, some 40 km southeast of Santa Rosalia, Baja California Sur, can produce over 2 million tonnes/year. Most of the production is shipped to wallboard manufacturers on the western seaboard of the United States and Canada. This is a perfect example of large-scale efficient mining operation close to a deep-water port, allowing a low-priced product to be competitive in the international market. Gypsum consumption in southern California can be used as a specific example. It is approximately 2,200 km from San Marcos Island in Baja California to Los Angeles. There are very high grade gypsum deposits in northwestern Arizona and southwestern Utah, about 565 km from the major gypsum consumers in the Los Angeles area. However, these US deposits cannot compete, because the cost of trucking from relatively nearby deposits is much higher than the transportation costs by ocean from San Marcos island.

## GRAPHITE (GRAFITO)

Production: 37,258 tonnes

US\$4,179,000

Exports: N.A. tonnes

US\$15,709,000

Imports: N.A. tonnes

US\$7,002,000

Comments: México ranks fifth in production of graphite in the world. Mines in Sonora produce amorphous graphite while the mine in Oaxaca produces crystalline graphite.

### Major Producers

Grafitera de Sonora, S.A.

Grafitos Mexicanos S.A.

Grafitos Industrializados Mexicanos SA de CV

Grafito Superior, S.A.

Exploradora Sonorense de Grafito, S.R.L.

Grafito de México, S.A.

### Mexico

#### Production of graphite



### Mine Locations

Southeast of Hermosillo, Sonora

Southeast of Hermosillo, Sonora

Southeast of Hermosillo, Sonora

Southeast of Hermosillo, Sonora

Southeast of Hermosillo, Sonora

Telxlatluhuaca, Oaxaca

Figure 14. Graphite production

## GYPSUM (YESO)

Production: 4,774,130 tonnes

US\$132,095,000

Exports: N.A. tonnes

US\$14,391,000

Imports: N.A. tonnes

US\$1,324,000

Comments: World's eleventh largest producer of gypsum with production in 16 of the 31 states in México. The material from San Marcos Island is principally consumed on the west coast of the United States.

### Major Producers

Compañía Occidental Mexicana, S.A.

Yeso Mexicano, S.A.

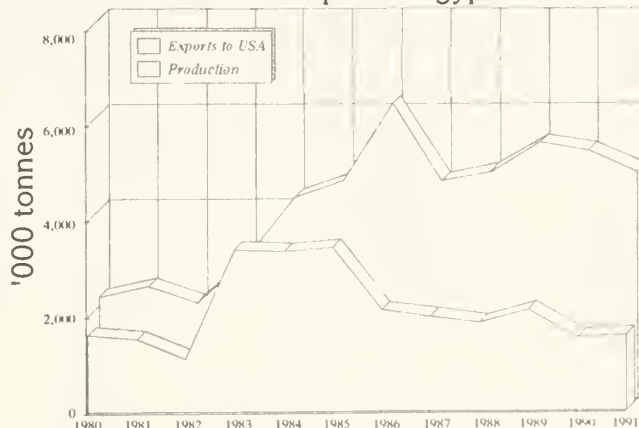
Yesera Monterrey, S.A.

Yeso El Tigre, S.A.

Yesera Nazas S.A.

### Mexico

#### Production & exports of gypsum



### Mine Locations

San Marcos Is., Baja California Sur

La Borreguita, San Luis Potosí

Mina, Nuevo León

Lagunillas de Rayón, Puebla

Matamoros, Coahuila, and Gómez Palacio, Durango

Figure 15. Gypsum production and exports to the USA.



PHOSPHATE ROCK (ROCA FOSFORICA)

Production: 596,332 tonnes  
US\$21,718,000  
Exports: Nominal  
Imports: N.A. tonnes  
US\$68,326,000

Comments: From a high of 835,000 tonnes production in 1988, production has dropped to less than 600,000 tonnes even though domestic demand continues to escalate. It is reported that Roca Fosfórica, owned by the government, is for sale.

Major Producers

Roca Fosfórica Mexicana, S.A.  
Minerales Industriales, S.A.

Mine Locations

San Juan de la Costa, Baja California Sur  
Zimapán, Hidalgo

Figure 16. Phosphate rock production.

All in all, recent Mexican gypsum exports to the United States have varied between 1.6 and 2.4 million tonnes/year, valued at US\$8 to 12 million (Table 10). This represents some 20% of US gypsum imports with Canada accounting for over 70%.

Table 10. Production & exports of gypsum in México ('000 tonnes).

	Gypsum production	Gypsum exports to the USA
1980	2,171	1,607
1981	2,390	1,513
1982	2,042	1,111
1983	2,958	3,373
1984	4,260	3,352
1985	4,602	3,430
1986	6,205	2,108
1987	4,575	1,979
1988	4,780	1,850
1989	5,390	2,118
1990	5,224	1,528
1991	4,774	1,580

Table 11. Phosphoric acid producers in México.

Producer	Location	Capacity Tonnes P <sub>2</sub> O <sub>5</sub>
Fertilizantes Mexicanos S.A.	Coatzacoalcos, Veracruz	417,000
	Lázaro Cárdenas, Michoacán	396,000
	Minatitlán, Veracruz	50,000
	Monclova, Coahuila	18,000
Industrias Químicas S.A.	Guadalajara, Jalisco	24,000
Total		905,000

PHOSPHATE ROCK (ROCA FOSFORICA)

More than 90% of the phosphate rock produced in the world goes into the manufacture of fertilizers, either singly (for example normal or triple superphosphate), or in combination with one or both of the other primary nutrients, potassium and nitrogen. The remaining 10% is consumed in a variety of industries, including the manufacture of detergents, animal feedstuffs, food and drink products, fire extinguishers and dental products, as well as in the surface treatment of metals.

México has the capacity to produce approximately 1 million tonnes/year of phosphate rock, which is quite modest by world standards. However, it makes a significant contribution to the domestic requirements of some 2 million tonnes/year of contained P<sub>2</sub>O<sub>5</sub>, and helps reduce import needs to about 1.5 million tonnes/year. Imports are largely from Florida and from Morocco.

Mexican phosphate production has traditionally been based on deposits associated with impure Jurassic limestone of the Sierra Madre Mountains in Hidalgo State. However, it appears that Minerales Industriales S.A.'s 200,000 tonnes/year mine at Zimapán closed in 1990. Consequently, the main supplier is now Roca Fosfórica Mexicana, S.A.'s San Juan de la Costa Mine in Baja California Sur (Figure 16). After conversion to an underground operation in 1986, and the installation of continuous miners, the mine can produce about 500,000 tonnes/

## SALT (SAL)

Production: 7,532,400 tonnes

US\$106,568,000

Exports: 6,076,900 tonnes

US\$ 91,002,000

Imports: Nominal

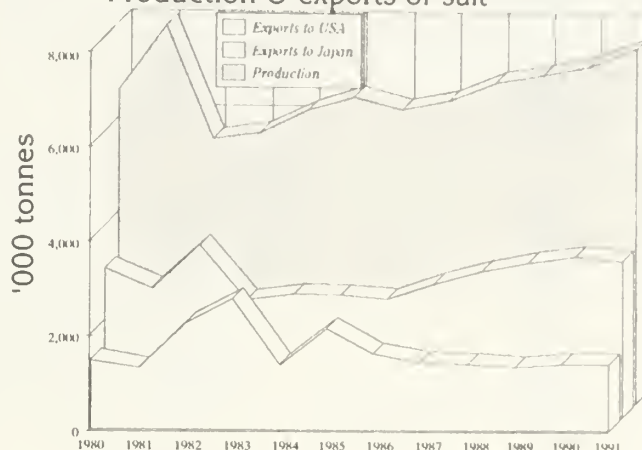
Comments: World's eighth largest salt producer and a large exporter. From a standing start in 1979, Exportadora has grown to its present size. There is talk of the government selling their 51% to private interests.

### Major Producers

Exportadora de Sal, S.A. (ESSA)

## Mexico

### Production & exports of salt



### Mine Locations

Guerrero Negro, Baja California Sur

Figure 17. Salt production and export.

year of concentrate. In the San Juan de la Costa deposit, about 50 million tonnes of phosphate reserves have been identified. The Santo Domingo deposit, a phosphatic beach sand covering an area of approximately 1,500 sq km, is being evaluated, although it is of marginal grade.

Production of phosphoric acid, a common intermediate product between phosphate rock and fertilizers, is dominated by Fertilizantes Mexicanos S.A., with four plants and 97% of the production capacity (Table 11).

## SALT (SAL)

The bulk of common salt is used in the chemical industry, in particular to produce numerous sodium and chlorine chemicals. The most important of these are the chloralkalis, chlorine and caustic soda, which are extracted from brine using electrolysis. Salt is used with limestone in the Solvay process to produce soda ash, and with sulfuric acid to yield hydrochloric acid and sodium sulfate. Other uses include a de-icing agent, a food preservative, as well as in a variety of other applications from the processing of textiles, to the manufacture of dyestuffs.

After the United States and Canada, México is the third largest salt producer in the Western Hemisphere. Perhaps even more important is the fact that of the 8 million tonnes/year produced, almost 80% is exported to the United States, Japan and other markets in the Pacific Rim, where it competes head-to-head with exports from Western Australia, and more recently Chile (Table 12, Figure 17).

A small percentage of the Mexican production comes from numerous deposits in the extension of the Permian Basin across the US border, particularly in the Cuchillo Parado area. In addition, there is production from Jurassic salt anticlines near Monterrey, that is used to make synthetic soda ash. Salt is also produced along with oil, gas and sulfur in the salt basin of the Isthmus of Tehuantepec, which extends for 275 km along the coastal plain from Veracruz southwards to Tabasco, and perhaps continues to the Yucatan Peninsula. This represents about 1.5 million tonnes of capacity divided between more than 100 small-scale producers.

Table 12. Production and exports of salt in México ('000 tonnes).

	Salt production	Salt exports to the USA	Salt exports to Japan
1980	6,575	1,460	3,105
1981	7,953	1,307	2,690
1982	5,561	2,249	2,599
1983	5,703	2,761	2,445
1984	6,167	1,387	2,570
1985	6,467	2,148	2,557
1986	6,205	1,611	2,484
1987	6,393	1,435	2,818
1988	6,788	1,412	3,076
1989	6,942	1,352	3,260
1990	7,135	1,412	3,379
1991	7,532	1,413	3,300

*Major salt movement in the Pacific Rim*

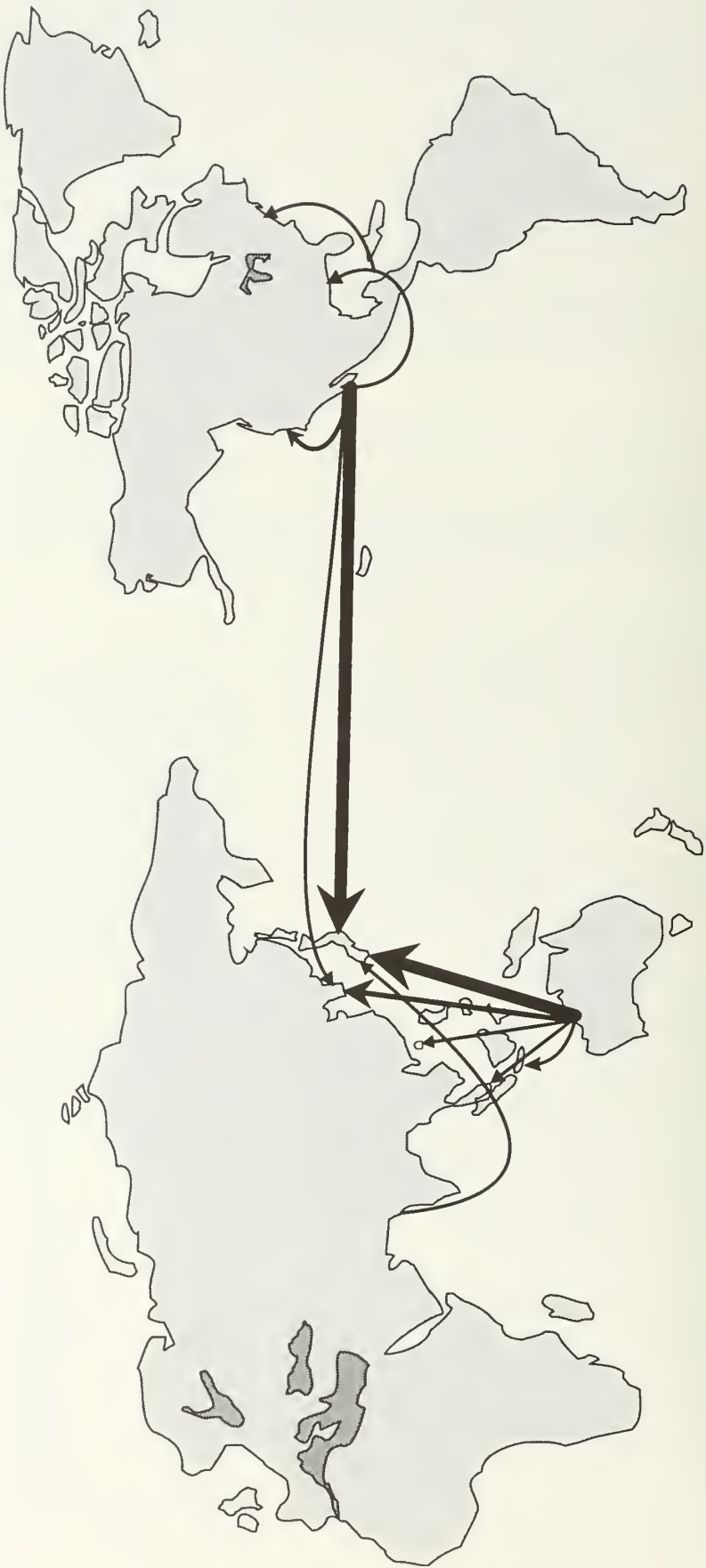


Figure 18. Major salt movement in the Pacific Rim.



## SODIUM SULFATE (SULFATO DE SODIO)

Production: 650,000 tonnes

US\$ - N.A.

Exports: 100,000 tonnes (estimated)

US\$ - N.A.

Imports: Nominal

Comments: *México is the world's leading producer of natural sodium sulfate with a capacity of almost 700,000 tonnes/year.*

### Major Producers

Química del Rey, S.A. de C.V.

### Mine Locations

Laguna del Rey, Coahuila

Figure 19. Sodium sulfate production.

In contrast, the bulk of México's commercial salt production, and virtually all of its exports comes from a single operation at Guerrero Negro in Baja California Sur. The facility, operated by Exportadora de Sal S.A. (ESSA), which is owned by the government's Fideicomiso de Fomento Minero (51%) and Mitsubishi (49%), includes 16,000 hectares of evaporating ponds yielding 5.5 million tonnes/year of 99.7% (dry) NaCl product. There are plans to expand production to 7 million tonnes/year by 1996. Most of the production is transported to the company's port complex at Cedros Island via 6,500 - 8,500 tonne barges operated by a wholly owned subsidiary of ESSA, Transportadora de Sal S.A. de C.V. Pier facilities at Cedros Island can accept vessels up to 165,000 DWT, and can load at a rate of about 30,000 tonnes/day. Exports to Japan, which account for 60% of sales, are via three company vessels: 150,000, 120,000 and 72,000 DWT. In Japan, Mitsubishi's Mitsuko Island, off Kure in the Sato Island Sea, contains a vast salt trans-shipment facility to serve smaller customers, via 10,000 tonne lighters. Like gypsum from nearby San Marcos Island, this is another example of large scale and low production costs, allowing a low-priced industrial minerals to penetrate the export market. Sales to the United States have been falling and currently account for less than 20% of the shipments. Other customers are Canada, Korea and New Zealand (Figure 18).

## SODIUM SULFATE (SULFATO DE SODIO)

Commercial sodium sulfate is produced either from natural deposits of glauberite ( $\text{Na}_2\text{SO}_4\text{CaSO}_4$ ), mirabilite ( $\text{Na}_2\text{SO}_4\cdot 10\text{H}_2\text{O}$ ) or thenardite ( $\text{Na}_2\text{SO}_4$ ), or as a byproduct of the manufacture of such industrial products as rayon, cellulose, lithium carbonate, boric acid and paper. The bulk of consumption is as an inert filler in granular detergents, and as a chemical in pulp and paper manufacture. Technical requirements for a "detergent-grade" sodium sulfate include particle size distribution, whiteness, a minimum of 99%  $\text{Na}_2\text{SO}_4$ , plus limits on moisture, water-insoluble material, iron, and chlorine. However, the market for sodium sulfate is declining rapidly, as compact powder and liquid detergents, which use little or no sodium sulfate,

become increasingly popular. Lower-grade material or "salt cake", with a minimum  $\text{Na}_2\text{SO}_4$  content of 97%, is used in kraft paper manufacture. This use is declining because of environmental considerations, and the increased use of emulsified sulfur and caustic soda. Minor uses of sodium sulfate include the manufacturing of glass, dyes, sulfonated oils, agricultural feedstocks, metallurgical fluxes, water-softening agents, leather tanning, and dynamite and safety explosives.

México is the world's leading producer of sodium sulfate accounting for 26% of the natural production, and 13% of the overall natural plus synthetic total. By far the largest Mexican producer is Química del Rey, a subsidiary of Industrias Peñoles, which extracts subsurface brine from Laguna del Rey, some 170 km north of Torreón, Coahuila. The operation has an annual capacity of more than 600,000 tonnes (Figure 19). This production allows México to be self sufficient in sodium sulfate, as well as a major exporter of sodium sulfate to the United States, Brazil and Venezuela.

Three small sodium sulfate producers in México have a combined capacity of less than 60,000 tonnes, Celanese Mexicana S.A. and Química Central S.A. (both synthetic producers), and Sulfato de Viesca S.A. in Coahuila. A large deposit of thenardite has been discovered in Sonora by a subsidiary of Vitro Química, Fibras y Minería, and is being evaluated.

## SULFUR (AZUFRE)

Sulfur and its derivatives are used at some point in virtually every known modern manufacturing process. Almost two-thirds of the total consumption is in the manufacture of phosphate fertilizers; the largest non-fertilizer consumer of sulfuric acid is the petroleum industry, where it is used as a catalyst in alkylation refining. Other major uses are in metal mining and processing, such as titanium dioxide production, via the sulfate route, and steel pickling. It is also used in the manufacture of pulp and paper, the vulcanization of rubber and the production of synthetic detergents.

SULFUR (AZUFRE)

Production: 2,122,482 tonnes  
US\$199,124,000

Exports: 1,335,874 tonnes  
US\$149,501,000

Imports N.A. tonnes  
US\$36,508,000

Comments: México ranks seventh in world production of sulfur, which includes Frasch by-product sulfur from oil and gas production and metallurgy. The Government owns 100% of Azufrera Panamericana and 66% of Exploradora. It is stated in the literature that the government is planning to privatize both companies.

Major Producers

SULFUR

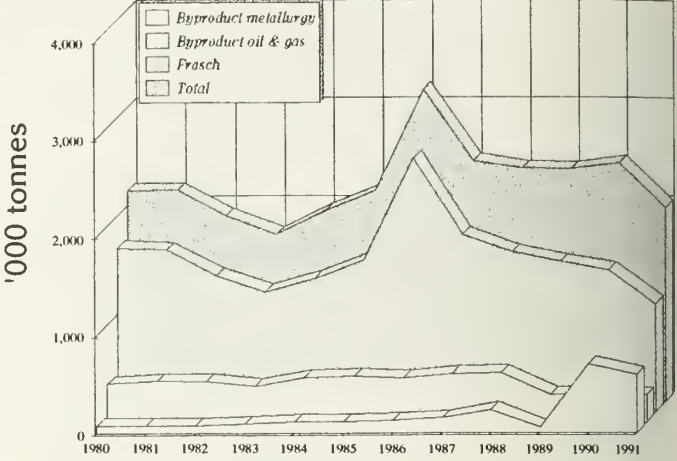
Azufrera Panamericana, S.A.  
Cía. Exploradora del Istmo, S.A.

SULFURIC ACID

Mexicana de Acido Sulfúrico S.A.  
Industrias Peñoles S.A.  
Grupo IMMSA

Mexico

Production of sulfur by form



Mine Locations

Jaltipán de Morelos and Coahuila, Veracruz  
Texistepec, Veracruz

Nacozari de García, Sonora  
Torreón, Coahuila  
San Luis Potosí, S.L.P.

Figure 20. Sulfur production

The worldwide production of recovered or by-product sulfur, derived from the refining of crude oil and natural gas, or the scrubbing of industrial stack gases, has grown in concert with environmental laws requiring that sulfur be extracted from various sour products or contaminated waste. By-product sulfur now constitutes 56% of world sulfur supply. The balance is produced from native sulfur, that is from sulfur concentrated in bedded deposits and salt-dome caprock, which is extracted by the Frasch process.

México has the capacity to produce approximately 2,775,000 tonnes of contained sulfur each year (equivalent to 4% of world production). In recent production which has been around 2,400,000 tonnes/year, 60% is Frasch sulfur, 29% as a byproduct from oil and gas refining and 11% as a byproduct of metallurgical processing (Table 13, Figure 20).

The belt of salt domes of Louisiana and Texas continues southward into México, and forms a large reservoir of

Table 13. Historical production of sulfur in México by form ('000 tonnes contained sulfur).

	Frasch	Byproduct oil & gas	Byproduct metallurgy	Total
1980	1,670	402	77	2,149
1981	1,652	426	76	2,153
1982	1,391	425	78	1,893
1983	1,225	377	101	1,703
1984	1,364	461	120	1,946
1985	1,551	475	120	2,146
1986	2,588	456	134	3,178
1987	1,806	501	154	2,461
1988	1,624	510	240	2,374
1989	1,528	286	555	2,369
1990	1,441	290	701	2,432
1991	1,100	280	600	1,980

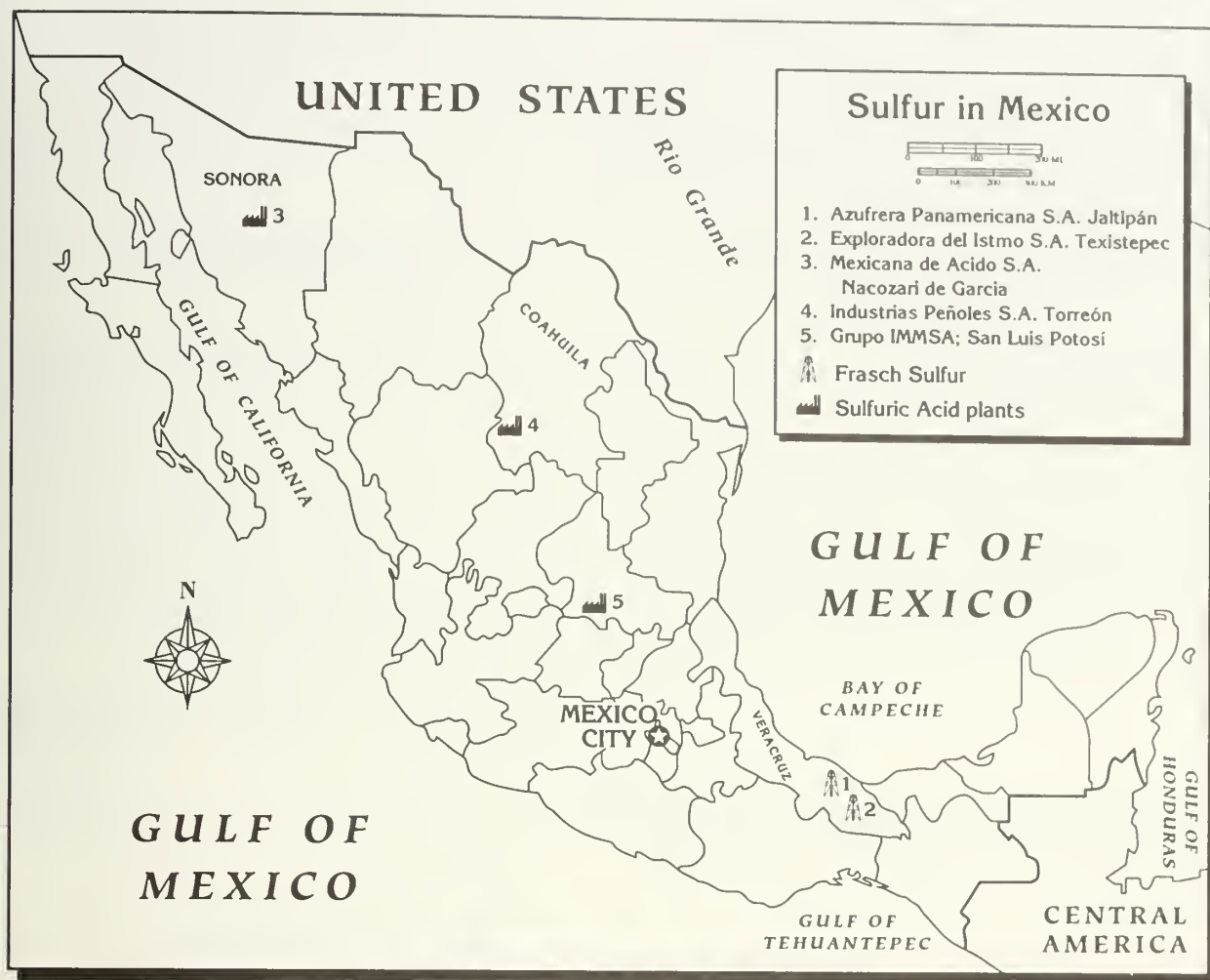


Figure 21. Sulfur processing sites.

oil, gas and sulfur. This basin covers around 51,800 sq km of México, about a fifth of which is offshore, and the remainder in the southeast part of Veracruz and northern Tabasco states. Generally, the salt domes are relatively shallow, and in the southwest and western parts, sulfur-bearing cap rocks have been found at the surface. Exploitation using the Frasch process began at the Jaltipán Dome in 1955, and this, together with Coahuila, Veracruz (400,000 tonnes/year) is exploited by Azufrera Panamericana, S.A. There is concern that technical problems at Coahuila may put its future in doubt. The other sulfur operation is Texistepec, a 700,000 tonnes/year mine operated by Cía. Exploradora del Istmo, S.A. (Figure 21).

Over the past ten years, except for the 1986/87 period, Frasch sulfur production in México has remained remarkably steady at 1.5 million tonnes/year. Byproduct sulfur

from oil and gas held steady at 400,000 to 500,000 tonnes/year until 1989, when lower oil and gas production halved the production rate. In contrast, byproduct sulfur from smelter plants has increased from less than 100,000 tonnes in 1980, to 600,000 to 700,000 tonnes in 1990/91. As a percentage of total Mexican sulfur production, smelter sulfur has increased from 3.5% in 1980, to over 30% in 1991. The increased supply is based on production from several large-scale smelters, which must comply with US emission standards. For example, at México's newest copper mine, Mexicana de Cobre S.A.'s La Caridad Mine at Nacozari de Garcia, Sonora (just 105 km south of Douglas, AZ), an affiliate company called Mexicana de Acido Sulfúrico S.A. has, since 1988, the capacity to produce 950,000 tonnes/year of sulfuric acid. Other important plants are Industrias Peñoles S.A.'s Torreón in Coahuila, and Grupo IMMSA at San Luis Potosí.



Other Mineral Production

In addition to the above mentioned mineral commodities, México also produces lesser amounts of other important industrial minerals and includes: diatomite, magnesite and magnesia, mica, perlite, sodium carbonate, talc, vermiculite and wollastonite (Figure 22).

INTERNATIONAL TRADE AND PARTICIPATION

México has been an active member of the international business community, especially since World War II. México and the United States have been interdependent in the business sphere for many years. This close relationship has included the export and import of industrial minerals between the two countries, as evidenced in the "Market Factors" and "Imports and Exports" sections of this paper. As with all trading nations, there have been disagreements, and the need for extensive trade negotiations, with respect to quantities of goods traded and tariffs imposed, but, for the most part México and the United States enjoy good

trade relationships. International membership by México includes:

- General Agreement on Tariffs and Trade (GATT). México has been a member of GATT since 1986.
- Latin American Association for Economic Integration (ALADI)
- Bi-lateral Trade Agreements with Central American Economic Block, South American Countries and Pacific Rim Countries

North American Free Trade Agreement (NAFTA), the United States of America and the United Mexican States have negotiated various trade agreements or treaties over the last few years. These included, in 1990, the General System of Preferences (GSP), which specified the importation into the U. S. of certain amounts of commodities on a duty-free basis. Also in 1990 the two countries agreed on a Free Trade Agreement (FTA), which broadened the objectives of trade. The U. S. and Canada had previously (1989) had a Free Trade Agreement.

In late 1990, Canada stated that they would like to participate in a North American Free Trade Agreement,

Figure 22. Other minerals' producers and locations.

<b>DIATOMITE (DIATOMITA)</b>	
<b>Major Producers</b> Almería S.A.  Filtrantes Técnicos S.A. Industrias Minomet S.A.  Comments: Almería S.A., an associate of Celite Corporation, has the capacity to produce around 45,000 tonnes/year of diatomite. Consumption is largely domestic.	<b>Mine Locations</b> Zacoalco de Torres, Jalisco (mine) Zacualpan and Naucalpan, México (plants) Naucalpan, México San Felipe del Progreso, México
<b>MAGNESITE &amp; MAGNESIA (MAGNESITA &amp; MAGNESIO)</b>	
<b>Major Producers</b> Química del Rey S.A. Química del Mar S.A.  Comments: Both companies are affiliates of Industrias Peñoles and both produce dead-burned grades for refractories and calcined grades for chemical use. Química del Rey S.A. produces 100,000 tonnes/year as a coproduct of sodium sulfate (see relevant section) and Química del Mar S.A. 70,000 tonnes/year from seawater.	<b>Mine Locations</b> Laguna del Rey (brine), Coahuila Ciudad Madero (seawater), Tamaulipas
<b>MICA (MICA)</b>	
<b>Major Producers</b> Demetrio Catellanos G. Gregorio Venegas Ríos Luz María Naravaez González  Comments: Production is around 6,000 tonnes/year.	<b>Mine Locations</b> San Miguel Ejutla, Oaxaca Miahuatlán, Oaxaca Nochixtlán, Oaxaca

Figure 22. Continued

**PERLITE (PERLITA)****Major Producers***Minera Oriental S.A.**Termolita S.A.**Aislantes del Pacífico S.A.***Mine Locations***Oriental, Puebla (mine) Near México D.F. (expansion plant)**Durango, Durango (mine) Monterrey, NL (expansion plant)**Ciudad Obregón, Sonora*

**Comments:** *Minera Oriental is an affiliate of Grefco Inc. of the United States. Production is approximately 40,000 tonnes/year virtually all for domestic use.*

**SODIUM CARBONATE (CARBONATO DE SODIO)****Major Producers***Sosa Texcoco S.A.**Industria del Alcalí S.A.***Mine Locations***Lake Texcoco, Ecatepec de Morelos, México**Santa Catarina, NL (Solvay)*

**Comments:** *Sosa Texcoco S.A. can produce 220,000 tonnes/year of soda ash from its plant at Ecatepec de Morelos on Lake Texcoco in the State of México, just north of México City. The company is adding a sodium bicarbonate production line. Industria del Alcalí S.A., a subsidiary of the large glass producer Vitro Química, Fibras y Minería, operates a 150,000 tonnes/year Solvay plant at Santa Catarina near Monterrey. Domestic consumption is supplemented with imports from the United States which have increased to almost 237,000 tonnes in 1991.*

**TALC (TALCO)****Major Producers***Grupo Técnico/**Sierra Talc de México S.A.***Mine Locations***Tehuiztzingo, Puebla (mine)**México D.F.; State of México; Monterrey, Nuevo León;**Guadalajara, Jalisco (all plants)*

**Comments:** *Grupo Técnico dominates talc in México through its mines and plants and its minority holding in Sierra Talc. Production varies between 15,000 and 30,000 tonnes/year. Imports, largely from the United States, exceed 100,000 tonnes/year.*

**VERMICULITE (VERMICULITA)****Major Producers***Aislamientos Técnicos S.A.**Comments:* *Production is several hundred tonnes/year.***Mine Locations***México D.F. (plant)***WOLLASTONITE (WOLLASTONITA)****Major Producers***Wollastonita de México S.A.**General de Minerales S.A.***Mine Locations***Guadalupe, Zacatecas**Pánfilo Natera, Zacatecas*

**Comments:** *Production is around 10,000 tonnes/year, mainly used in the Mexican ceramics industry.*

which would be composed of Canada, the United States and México. NAFTA negotiations still continue between the three countries. The principal question in the U. S., in 1993, is whether the Congress of the United States will ratify the agreement.<sup>1</sup>

At present, foreign firms can only own 49% of a mining company, or the foreign company can own 100% of a mining company by establishing an investors trust (fideicomiso), wherein the foreign company owns the stock in the trust, and the trust owns the mining property or rights. However, there have recently been articles in

<sup>1</sup>U.S. Congress passed NAFTA in November, 1993

various Mexican periodicals, which have addressed the subject of NAFTA, and possible revisions to the investment laws, that would be more lenient toward foreign investors. An article, of this type, was written by a Mexican lawyer, and published in the April, 1993, issue of *Baja Times*. We quote from this source, because the article appeared in English:

The Congress of México is considering legislation that liberalizes investment by foreigners, "In an effort to implement the policy and spirit of NAFTA, for each member country to provide investors from the other member countries with 'fair and equitable treatment and full protection and security...' for their investments".

These revisions will liberalize restrictions on foreign investment. This statement is also from the *Baja Times* article:

"While ownership by foreigners in the following industries and activities will be limited to 49%, where foreign capital exceeds 49%, a permit or authorization may be obtained to exceed that percentage of foreign ownership: construction, mining, oil and gas drilling, fishing, maritime transportation, loading and unloading services for maritime transportation, air navigation, airport and heliport administration, private educations and legal services".

A non-legal interpretation by the authors is that, sometime in the future, an investor's trust may no longer be needed. This will save the foreign investor's trustee fees, and eliminate the risk inherent in the investor trust-type of ownership.

It should be noted, that the *Baja Times* article printed the following warning in bold letters:

"Please remember, that this legislation stands proposed, and has not been enacted into law at this point in time!"

Nevertheless, the fact that legislation of this type is being considered by the México Congress, and the fact that United States and Canadian mining companies have recently commenced a mini-mining rush to Mexico, indicates that a new "golden age" of mining is dawning.

IMPORTS AND EXPORTS

Table 4 summarizes the production of selected industrial minerals. Figure 30 and Tables 14 and 15 summarize imports, and Tables 16 and 17 and Figure 31 summarize exports of industrial minerals. It is obvious that a significant proportion of the industrial minerals produced in

Mexico  
Trade balance in industrial minerals

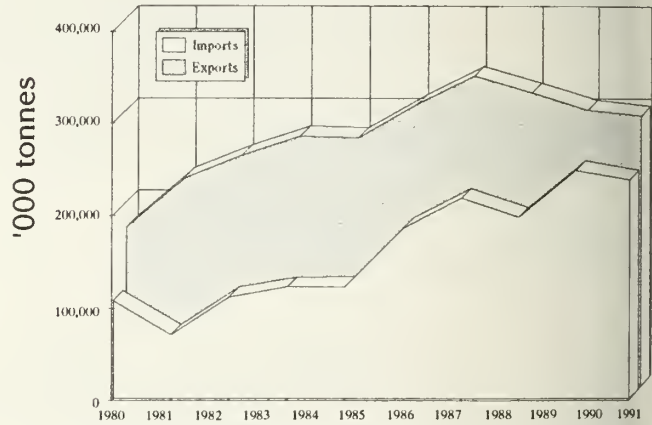
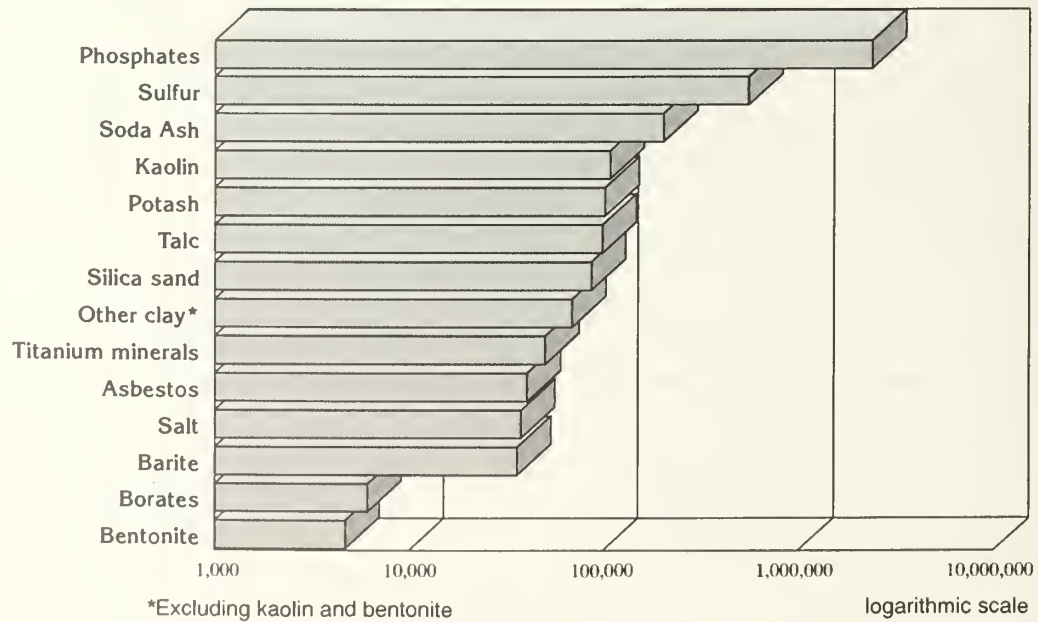


Figure 24. México's trade balance in industrial minerals.



\*Excluding kaolin and bentonite

Figure 23. Important industrial mineral imports (tonnes).



Table 14. Imports (tonnes)

	1986	1987	1988	1989	1990
Abrasives	1,120	988	542	452	300
Alumina	37,611	26,011	32,131	34,501	42,510
Asbestos	28,339	38,457	34,055	35,428	39,316
Barite	110	88	58	233	36,060
Bauxite	35,086	40,268	53,039	51,244	46,023
Bentonite	612	2,162	2,950	2,900	4,670
Borates	975	167	113	2,149	1,088
Calcium carbonate	1,519	1,358	1,445	2,249	2,747
Clays	129,539	147,075	170,088	181,820	176,690
Diatomite	546	423	595	2,095	519
Feldspar	610	581	522	1,445	1,431
Fuller's Earth	8	2	102	37	NA
Graphite	48	401	1,181	1,229	1,698
Gypsum	8,546	5,767	34,322	15,025	12,015
Kaolin	93,125	98,546	110,688	107,638	104,560
Magnesia	7	47	4,826	12,982	28,112
Manganese	112,353	186,380	140,333	167,578	137,416
Marble	1,192	1,952	2,364	3,243	2,924
Mica	268	141	199	206	280
Phosphate	1,096,766	1,345,436	1,489,631	1,456,615	2,278,380
Potash	174,313	59,950	155,739	110,372	97,686
Salt	737	680	1,061	7,375	37,247
Silica	82,655	76,779	74,995	81,712	84,334
Sulfur	329,972	681,193	605,277	285,277	517,527
Talc	96,200	120,854	107,593	109,965	97,137
Vermiculite	462	942	206	627	1,730

Source: Anuario Estadístico del Comercio Exterior de los Estados Unidos Mexicanos

Table 15. Imports (N\$'000).

	1987	1988	1989	1990	1991
Abrasives	454	567	5,764	11,462	22,391
Alumina	42,370	44,315	145,719	175,383	138,236
Asbestos	24,947	38,173	43,121	58,545	56,472
Barite	41	117	286	3,490	12,771
Bentonite	640	844	1,426	1,781	5,149
Borates	776	2,293	23,087	27,678	28,249
Calcium carbonate	443	1,022	7,569	11,306	12,315
Celestite	-	-	472	20	766
Clays*	9,162	29,891	36,435	37,445	43,300
Diatomite	57	120	1,527	639	392
Dolomite	36	1,890	1,575	1,930	8,142
Feldspar	36	44	399	359	391
Fluorspar	10	19	26	146	3,936
Fuller's Earth	1	60	32	519	470
Graphite	696	3,158	14,825	19,097	21,004
Gypsum	740	3,168	2,162	1,993	3,972
Kaolin	13,808	36,512	44,523	46,434	52,300
Limestone	-	-	1,742	1,426	52,300
Magnesia	11	8,170	21,433	40,521	40,152
Manganese	3,842	4,716	1,989	1,830	23,348
Marble	617	1,114	12,079	18,293	32,071
Mica	1,184	659	3,552	3,056	5,904
Perlite	-	-	18	43	187
Phosphate	50,054	115,258	125,452	232,079	204,977
Salt	157	589	2,159	6,548	13,704
Sand & gravel	454	567	5,764	11,462	22,391
Silica	2,594	4,015	8,580	13,697	22,728
Sulfur	81,514	134,255	76,056	129,268	109,523
Talc	5,237	17,567	14,769	14,260	18,822
Vermiculite	315	178	823	1,817	1,451
Vollastonite	-	-	-	-	-
Zircon	401	2,197	17,333	9,807	17,660

\* comprises ceramic and refractory clays

Table 16. Exports (tonnes).

	1986	1987	1988	1989	1990
Alumina	12,079	13,382	18,921	11,964	18,166
Barite	29,791	65,944	44,633	54,243	41,161
Bentonite	11,488	11,845	3,074	5,345	1,126
Celestite	30,833	39,324	42,159	44,852	45,249
Clays*	57	111	222	126	106
Diatomite	5,460	5,749	6,114	7,986	5,106
Dolomite	1,481	2,165	2,031	1,062	769
Feldspar	688	3,733	5,407	11,764	10,307
Fluorspar	437,591	474,779	509,443	554,390	379,066
Fuller's Earth	23,070	22,225	11,977	2	6
Graphite	18,960	19,647	25,321	25,296	18,688
Gypsum	2,337,522	2,183,697	2,241,221	2,603,744	1,519,593
Kaolin	2,012	83	53	277	92
Magnesia	4	31	33,243	84,722	64,128
Manganese	123,670	165,326	169,126	127,227	65,263
Marble	3,057	1,485	5,027	5,159	23,274
Perlite	3,140	2,372	2,230	118	142
Phosphate	437	0	0	0	0
Salt	4,440,481	4,994,944	5,098,126	5,526,458	4,849,273
Silica	11,070	9,365	52,909	31,171	13,677
Sulfur	1,047,367	1,444,621	1,738,934	1,208,901	1,330,909
Talc	20	115	292	245	255
Wollastonite	2	164	0	0	0

\* comprises ceramic and refractory clays

Source: Anuario Estadístico del Comercio Exterior de los Estados Unidos Mexicanos

Table 17. Exports (N\$'000).

	1987	1988	1989	1990	1991
Abrasives	1,798	6,261	12,331	12,148	20,531
Alumina	206	147	1,081	1,343	791
Asbestos	-	-	-	-	-
Barite	1,798	2,151	5,363	5,563	5,606
Bentonite	227	870	960	462	25
Borates	-	-	27	40	25
Calcium carbonate	-	-	375	650	701
Celestite	4,491	6,276	7,324	9,794	8,080
Clays*	47	136	136	134	230
Diatomite	2,696	4,805	47,098	4,902	4,435
Dolomite	245	383	274	246	167
Feldspar	585	1,554	2,066	9,188	4,822
Fluorspar	46,916	95,036	124,482	103,593	64,186
Fuller's Earth	7,101	483	4	12	1
Graphite	2,993	22,301	41,008	50,899	47,126
Gypsum	15,973	29,084	38,568	34,380	43,173
Kaolin	25	29	75	23	91
Limestone	264	150	2,341	4,182	20,034
Magnesia	36	48,323	64,038	62,796	74,457
Manganese	13,875	24,054	27,734	22,383	16,112
Marble	449	1,885	37,218	45,937	76,593
Mica	3,419	6,228	4,510	5,863	5,587
Perlite	1,074	70	42	57	436
Phosphate	-	3	-	-	-
Salt	75,022	129,312	161,622	222,744	223,007
Sand & gravel	5	168	456	11,519	29,263
Silica	3,017	444	182	123	666
Sulfur	214,910	414,908	359,388	411,608	449,587
Talc	30	113	90	48	89
Vermiculite	9	1,429	390	180	212
Wollastonite	17	-	-	-	-
Zircon	-	-	726	1,413	1,461
<b>Total</b>	<b>403,663</b>	<b>782,364</b>	<b>903,399</b>	<b>1,069,256</b>	<b>1,123,560</b>

\* comprises ceramic and refractory clays

México is for the export market, in particular, celestite (plus strontium carbonate), fluorspar (plus hydrofluoric acid), gypsum (plus wallboard), salt and sulfur. These exports, and others, indicate the close relationship between México and the United States. Shipments from México to the United States account for approximately: 99% of the graphite exported by México; 75% of the hydrofluoric acid; 60% of the celestite, sodium sulfate and sulfur; 33% of the fluorspar and the gypsum; and 19% of the salt. México is also well placed to serve the expanding Pacific Rim markets: in particular, Japan, Korea and Taiwan.

On the other side of the coin, México imports significant tonnages of minerals. These include (1) bauxite and alumina for metal, abrasive, chemical and refractory manufacture; (2) clays and talc for a variety of industrial uses; (3) asbestos for construction and brake linings; (4) phosphate rock and potash for fertilizer manufacture and (5) silica sand, borates and soda ash for the glass and ceramics industries. Domestic production of minerals like calcium carbonate, perlite, diatomite and wollastonite is adequate for domestic demands.

## OPPORTUNITIES

It is obvious from the foregoing discussion, that México is very well placed to serve North American and world markets with a variety of industrial minerals, and their derivatives. Low-cost production on a large-scale has allowed salt, gypsum and cement to enter international trade; capital investment has added value to fluorspar (through HF production) and celestite (strontium carbonate). Large tonnages of Mexican limestone enters the United States in the form of cement. Demand for industrial minerals should continue to increase in a country with a 90 million and growing population; NAFTA will increase this market by more than 370 million people. Pacific-coast ports can supply the fast growing needs of the Pacific Rim, while certain minerals can reach Europe competitively. The recent and continuing changes outlined in the text, still further enhance the prospects for business opportunities in México's industrial minerals sector.

## Privatization

There are also opportunities through the privatization of existing companies. Candidates for divestment include: (1) the sulfur producers, Azufrera Panamericana S.A. (100% government owned) and Cía. Exploradora del Sulfuro, S.A. (66%); (2) the phosphate producer, Roca Fosfórica and (3) the salt producer, Exportadora de Sal, S.A. (51% government owned and 49% Mitsubishi).

## Import substitution/exploration targets

There are opportunities for import substitution, either through grass-roots exploration and development, or the expansion of existing production units. The following is a brief review of the more obvious possibilities:

### Abrasives, natural

Garnet and pumice are required in México to replace the imports of natural abrasives. In many cases, garnet is associated with wollastonite.

### Bauxite and alumina

México imports approximately 50,000 tonnes/year of bauxite, and 200,000 tonnes/year of alumina, mainly from the United States. Some refractory-grade bauxite is imported from Guyana.

### Borates

Approximately 3,000 tonnes/year each of colemanite and boric acid, are imported for use in glass and ceramics. A colemanite deposit north of Hermosillo, Sonora, continues to be evaluated by Materias Primas Magdalena, a subsidiary of Vitro Química, Fibras y Minería. Formerly, this was a joint venture with US Borax Inc.

### Clays

Clays are a prime target for import substitution, through increased domestic production. The United States exports to México over (1) 100,000 tonnes/year of kaolin, valued at over US\$13 million; (2) 60,000 tonnes/year of ball clay, valued at US\$2 million; (3) 41,000 tonnes/year of fireclay, valued at almost US\$3 million and (4) 5,000 tonnes/year of bentonite, valued at almost US\$0.5 million.

### Calcium carbonate

Consumption of high-quality calcium carbonate is growing throughout the world. Increased production could serve the growing market in México, and if it is of sufficient quality, there are export possibilities in the western United States and the Pacific Rim markets.

### Dimension stone

The search for good quality and unusual dimension stone continues throughout the world, as the demand for granite, marble, limestone, sandstone and slate etc. expands. México has a tradition of using dimension stone, and could tap the growing markets in North America and the Pacific Rim, especially with the addition of advanced mechanical processing techniques.



## Fertilizer minerals

In the fertilizer area, México's production of phosphates falls far short of domestic demand, and there is no potash production. The 600,000 tonnes/year of domestic phosphate rock production is supplemented with 1.5 to 2 million tonnes plus of imports, mainly from Morocco and the United States. In addition, México imports upgraded phosphates, such as diammonium phosphate and monoammonium phosphate. Roca Fosfórica, the main phosphate producer in México, may be for sale. Imports of potash have varied from 100,000 to 150,000 tonnes/year, largely from the United States and Canada.

## Graphite

Although México is a major producer of amorphous graphite, flake graphite production from Oaxaca is fairly modest. Additional sources of flake graphite would be welcomed.

## Gypsum

Although México is a large-scale exporter of gypsum from Baja California, it is conceivable that similar deposits close to markets or deep-water ports could be economical.

## Kyanite minerals

There are some imports of kyanite from the United States, plus 2,000 tonnes/year of mullite.

## Perlite

The presence of crystalline silica in diatomite, and the relative absence of same in perlite, is allowing perlite to capture increasing proportions of the filter-aid market in the United States. If stricter environmental regulations are instituted as part of the NAFTA agreement, there could be an enlarged requirement for filter aid perlite in México.

## Salt

There is a possibility that the government will privatize its 51% share in Exportadora de Sal, S.A. (ESSA), which operates the Guerrero Negro, Baja California Sur, deposit.

## Soda ash

Domestic soda ash production required by the Mexican glass industry is supplemented by large imports from the United States. In 1991, the US shipped a record 236,957 tonnes to México. Trona is a prime exploration target in México.

## Talc

Talc imports from the United States exceed 100,000 tonnes/year. This is used in a wide variety of industries, which would prefer a domestic source.

## Titanium minerals

Up to 50,000 tonnes/year of titanium minerals are imported, mainly ilmenite from Australia, as a feedstock for Du Pont's titanium dioxide pigment plant. Florida-type mineral sand deposits would be a target.

## Wollastonite

Wollastonite, produced in México, is used in the domestic ceramics industry. However, there is some potential for increased production of high-aspect ratio grades, which could be exported to the United States and the Pacific Rim markets. In particular, the Pilares and San Martín deposits some 50 mi northwest of Hermosillo, Sonora, have been evaluated by several companies. The San Martín deposit is being leased by a subsidiary of Cominco.

## Positive outlook

Regardless of the outcome of the NAFTA ratification, the possibility of ratification of NAFTA and the beneficial attitude of the Salinas de Gortari government toward U.S.-Mexican relationships, as well as the favorable treatment of mining development in México by the government, have spurred a high level of interest and activity in the mining sector in México. This interest in México is assisted by the increasingly difficult conditions attendant to mining ventures, and especially new mines, in the United States and Canada.

Numerous US and Canadian mining companies have established offices in México, mainly in the Federal District (Distrito Federal), and exploration activities by these groups are being carried on throughout the country. A great deal of this activity is centered on precious and base metals, but these metal mining companies are starting to show an interest in México's nonmetallic minerals. Also, there are always the traditional industrial mineral companies in the United States and Canada, who are now exploring for opportunities to expand and develop in México.

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# APPENDIX 1

## POSTER ABSTRACTS

(Listed alphabetically by first author; \* = poster, \*\* = paper and poster.)

### GEOLOGY AND POTENTIAL OF INDUSTRIAL MINERALS IN MÉXICO

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The Republic of México is the world's largest producer of celestite, second in fluorspar and barite, and a significant producer of many others, including salt, sulfur, graphite, gypsum, bentonite, feldspar, perlite, diatomite, phosphate rock, silica sand, and sodium sulfate. New production may be brought on stream for borates, wollastonite, garnet, calcium carbonate and others.

The country covers a geographic area of 2 million square kilometers (760,000 square miles) and is divided into 15 physiographic provinces. More than 60 percent has been explored in detail for either nonmetallic or metallic minerals. This leaves large areas available for the discovery of world-class industrial mineral deposits. In addition to new deposits of those minerals currently being produced, there is exploration and development potential for borates, magnesite, rare earths, nepheline syenite, heavy mineral sands and numerous others.

# A COMMUNICATION GAP—A BREAKDOWN IN EFFICIENCY AND ITS COSTS TO USER, PRODUCER, AND EXPLORATIONIST

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The flow of mineral resources from the ground to the end user involves three major players; user, producer and explorationist/mine geologist.

The user may be a manufacturer who utilizes mineral resources to make industrial products that go directly to the market place or produces material used by others. Customarily, the user will specify to the mining company the technical standards required of processed minerals or rock that is shipped.

The mining company has the primary responsibility of ensuring the material it produces will satisfy the demands set forth by the user. This generally requires grade control at the mine and quality control at the mill site. If the company intends to remain in business, provisions must also be made to replenish reserves and find new deposits to provide for growth.

The explorationist/mine geologist has a fundamental responsibility to apprise management of the company's reserve position and assist in grade control at the mine site. The geologist plays a vital role in prospecting for new reserves either at the mine or elsewhere as needed.

Poor communication between the user, miner, and explorationist/mine geologist is a common and costly problem for all three parties involved. The miner and geologist need to have a clear understanding of technical standards established by the user. With this knowledge, the miner and geologist are in a better position to recommend changes in specifications that could lead to cost reductions for the user or to suggest alternative materials which would better satisfy the user's requirements.

The miner needs to inform the user of the various aspects of mining, processing, storage, and shipping with which he is confronted and how these relate to the delivered cost of the processed minerals. With this information, the user may be in a position to undertake changes in specifications or offer suggestions that could result in lower costs to either or both parties. The miner also should provide this information to the geologist and discuss other mining/processing options which may be available together with their costs. The geologist is then better prepared to recommend an alternative approach to mining that would allow for expansion of reserves or reduction in costs. If the geologist has a clear understanding of technical standards set forth by the user, he can call attention to other types of minerals or rocks that may satisfy the standards at a lower cost or even better material that could be used.

Failure to address the communication gap leads to inefficiencies and is generally very costly to all parties involved. In order to overcome this gap, the user should arrange for the mineral producer and geologist to visit their facility and show how processed minerals shipped to them fit into operations and the necessity for required specifications. All three parties need to discuss the technical limitations with which they are confronted. Often this can result in ideas or operational changes that are beneficial and result in increased efficiency along with cost reductions.

The universities and technical schools have an important role to fulfill. They need to develop a genetic system for classification of industrial mineral deposits similar to that used by explorationists who prospect for metal deposits. It would also be of considerable value to provide an integrated survey course that deals with industrial mineral deposits, mining engineering, mineral processing, and engineering economics so that the user, producer, and geologist can better communicate among themselves and improve upon their respective ability to carry out their responsibilities.

## GEM-MATERIAL PRODUCTION IN THE UNITED STATES\*

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Each year, individuals and companies in the United States produce a wide variety of natural, synthetic, and simulated gem materials. These materials are used for the manufacture of gems and art objects, for metaphysical purposes, for display in collections, and for certain industrial uses. Production of natural gem materials in the United States is represented by both mineral and organic materials. These include most of the better-known gem minerals, as well as the organic gem materials, pearl, shell, mother-of-pearl, coral, jet, and amber. It must be noted that U.S. production of diamonds, emeralds, and rubies is extremely limited. The U.S. does produce most, if not all, of the different types of synthetic gem materials and gem simulants currently available in the marketplace.

The variety of materials produced in the United States may be as diverse as that from any other country in the world, and that produced in California is as diverse as that from any State. But the United States is the leading producer of possibly only three gem materials: peridot, turquoise, and jasper. In addition, the value of U.S. gem material production traditionally has lagged behind that of most other producing countries.

The estimated value of U.S. gem materials produced during 1992 was \$51.2 million for natural materials and \$18.2 million for synthetics and simulants, according to the U.S. Bureau of Mines. Production in the United States may appear to be greater than that reported from certain other producing countries only because of disparities in the record-keeping and reporting systems. Also, production is understated in some countries because the materials are processed and marketed through unofficial channels.



# GEOLOGY, PRODUCTION, AND MARKETING OF PERLITE FROM THE WESTERN UNITED STATES

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Perlite occurrences in the United States are associated only with the volcanic terranes of the western states. Occurrences are in Tertiary through middle Quaternary volcanic rocks such as the glassy parts of silicic domes and flows, chill margins of dikes, sills, plugs and laccoliths, and welded ash-flow tuffs. Perlite is a silicic, rhyolitic volcanic glass with 2 to 5 wt % combined water. It is distinguished by the presence of either a granular texture or a vitreous, pearly luster from onion-skin-like fractures. It is obsidian further hydrated primarily by gradual post-emplacement hydration of glass with the addition of meteoric water into the glass-silica structure. Hydration may be partly due to resorption of exsolved magmatic water during or shortly after emplacement.

In 1991, perlite was mined by nine companies at 12 operations in six western states and was expanded at 62 plants in 33 states, most of which are not in the states where perlite is mined. New Mexico accounts for about 85% of the total tonnage mined. The remaining 15% comes from Arizona, California, Colorado, Idaho, and Nevada. Domestic production was an estimated 839,000 short tons (st). Owing to the low bulk density of expanded perlite, crushed and sized but unexpanded perlite is shipped directly to local markets for expansion and processing near end users. Value added to perlite is done primarily by expansion, and high value perlite products—such as microspheres or treated perlite—are also produced. Domestic apparent consumption of expanded perlite was 498,000 st, and the value of expanded perlite was \$101,695,000 for an average value of about \$202 per ton compared to about \$27 per ton unexpanded. Construction uses of expanded perlite accounted for 65% of total domestic sales. Expanded perlite used as filter aids, fillers, and in agriculture accounted for 32% of sales. Leading states for expanded perlite production, in descending order of sales were Mississippi, Pennsylvania, California, Illinois, and Georgia.

Domestic perlite delivered by truck or rail encounters transportation disadvantages in some areas of the eastern United States compared to perlite imported by ship primarily from Greece. In 1991, western U.S. perlite exports to Canada (about 32,000 st) offset much of Greek imports (about 60,000 st) and the net import reliance was about 5% of domestic perlite consumption. Most internationally traded perlite is unexpanded.

## COMMUNICATION IN DIVERSITY

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The field of industrial minerals and rocks includes such a wide diversity of materials and occurrences that communication is essential to foster a sense of 'belonging' among geologists and other professionals. Besides, exchange of ideas and information is desirable to help meet the needs of an ever-expanding world economy. A survey of the field shows to what an extent such communication—especially in the form of conferences and their proceedings—has increased during the past 25 years.

## GEOLOGY OF WESTERN U.S. TALC DEPOSITS

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California was a leading talc producing State until the late 1980s when production from the deposits in the Death Valley area ceased because of pressure to discontinue mining in and around Death Valley National Monument and because of health concerns affecting markets for tremolitic talc. Now the states of Montana and Texas account for slightly more than half of the U.S. talc production.

Deposits in an area encompassing the southern Death Valley and extending east into the Kingston Range were formed by contact metamorphism of carbonate beds in the Precambrian Crystal Spring Formation next to Precambrian diabase sills. These deposits contain ore ranging from high-purity, fine-grained talc to platy, tremolitic talc with a high brightness. Deposits of tremolitic talc and talc schist in the Silver Lake district in San Bernardino County resulted from contact metamorphism of Precambrian carbonate beds intruded by granitic plutons. Northeast in Esmeralda County, Nevada hydrothermal alteration related to Late Jurassic plutons caused talc replacement of Precambrian to Early Cambrian dolomite. A hydrothermal origin is also indicated for talc deposits in the Inyo Range just north of the Death Valley district. Here bodies of unusually pure talc occur in Paleozoic limestone near Jurassic granitic plutons. Talc is now mined from a deposit in the foothills of the Sierra Nevada Range east of San Francisco, where quartz-mica schist of the Permian Calaveras Formation has been hydrothermally altered to talc.

Replacement of magnesite in the Precambrian Allamoore Formation produced talc deposits now mined in the Allamoore district of west Texas. This dark-gray talc with a low iron content and containing carbonaceous material and dolomite is ideally suited for use in ceramics where it makes a white product when fired. Next to basic intrusions contact metamorphism has altered this dark-gray talc to a platy light-pink to white talc suitable for use as an extender in paint. Talc has replaced impure carbonate rocks and serpentine in the Llano district of central Texas.

All Montana talc production is from deposits in the southwestern part of the state that have been formed by Precambrian hydrothermal alteration of Archean dolomitic marble. This alteration has produced talc with high purity that ranges from very fine-grained, massive talc to coarser grained foliated talc. Markets include pitch control in paper, cosmetics, ceramics, rubber and plastics.

In southwestern and northeastern Oregon talc has replaced serpentine in the vicinity of Mesozoic plutons. Soapstone for carving is mined from a southwestern Oregon deposit. Deposits similar in origin occur in central and in northwestern Washington.

## CELITE CORPORATION'S DIATOMITE QUARRY LOMPOC, CALIFORNIA

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No abstract submitted.

# **GEOLOGY, GENESIS, AND MINING OF HIGH BRIGHTNESS, HIGH PURITY LIMESTONE DEPOSITS IN THE SAN BERNARDINO MOUNTAINS AND MOJAVE DESERT AREA OF SOUTHERN CALIFORNIA**

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The San Bernardino Mountains and Mojave Desert area of southern California contain the largest high brightness, high purity limestone mining operations and undeveloped reserves in western North America. Combined annual production of high brightness limestone products from several open pit mines is approximately 1.5 million tons, with an estimated gross value of \$75 million dollars per year. Pfizer Inc., Pluess-Staufer (California), Inc., and Partins Limestone (Riverside Cement), are the major producers. An additional 5.0 million tons of cement grade limestone is mined by several large cement producers in the Mojave Desert area.

High purity, high brightness limestone deposits in the San Bernardino Mountains and Mojave Desert region occur in Upper Paleozoic carbonate rocks which are part of an Upper Precambrian and Paleozoic sequence that unconformably overlies crystalline basement. The Paleozoic strata are divided into formations and members, and correlated with strata of the inner Cordilleran miogeocline. The region has been affected by multiple Mesozoic intrusive, contact, and regional metamorphic events. Structure is complex, and includes polyphase Mesozoic folding and thrusting, and complex Cenozoic structures. The area continues to be seismically active.

High brightness (white), high purity crystalline limestone deposits are uncommon because their formation is dependent on several geologic processes which include; 1) depositional environment, 2) contact and or regional metamorphism, 3) folding and faulting, 4) uplift and erosion, and 5) preservation through geologic time. The complex geologic history of the San Bernardino Mountains and Mojave Desert region has allowed the formation of several large high brightness, high purity limestone deposits which are currently being mined or will be mined in the future.

Pluess-Staufer (California), Inc. produces high brightness, high purity limestone from several quarries in the San Bernardino Mountains. These active mines combined with undeveloped deposits controlled by Pluess-Staufer in the San Bernardino Mountains, New York Mountains, and Bristol Mountains in the Mojave area, contain proven and or indicated reserves sufficient to sustain production well into the 21st century.

Pfizer Inc. currently mines from a large open pit quarry in the San Bernardino Mountains, and also controls large undeveloped deposits in the San Bernardino Mountains and Mojave Desert area, with combined reserves sufficient for many years.

Detailed geologic mapping, intimate knowledge of stratigraphy, recognition of complex structures, sampling, drilling and assay data, are proven tools in the discovery and delineation of high brightness, high purity limestone deposits in the San Bernardino Mountains and Mojave Desert region of southern California.

## **LIVINGSTON-GRAHAM'S AGGREGATE OPERATIONS, IRWINDALE, CALIFORNIA**

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## 1992 INDUSTRIAL MINERAL PRODUCTION IN CALIFORNIA AND NEVADA

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Together, California and Nevada accounted for about 10% of the nation's 1992 industrial minerals production. California was the leading state in industrial mineral production value with an estimated value of nearly \$2 billion. Nevada ranked 30th among the states with an estimated value of about \$240 million.

In total value of U.S. nonfuel mineral production estimated for 1992 by the U.S. Bureau of Mines, California ranked second and Nevada ranked third behind Arizona (the leading state in the nation) which produced just over \$3 billion. But 81% of California's total production value was derived from industrial minerals while only 10% of Nevada's total production value was derived from industrial minerals.

California led all other states in the production of boron minerals, portland cement, diatomite, calcined gypsum and construction sand and gravel, and ranked second in potash and soda ash production. Nevada was the leading producer of barite and mined magnesite, and ranked second in diatomite and lithium production.

California's five leading industrial minerals in terms of value were portland cement, construction sand and gravel, boron, crushed stone, and soda ash. Nevada's five leading industrial minerals in terms of value were construction sand and gravel, portland cement, diatomite, lime, and gypsum.

California had 13 additional industrial minerals reporting sales over \$1 million including, industrial sand and gravel, magnesium compounds, lime, salt, potash, natural sodium sulfate, clay, feldspar, crude gypsum, pumice, dimension stone, calcium chloride and perlite. Other Nevada industrial minerals reporting sales of better than \$1 million were lithium, industrial sand and gravel, crushed stone, mined magnesite, barite, and clay.

## SOLUTION RECOVERY OF PHOSPHATE FROM DEEP WELLS IN ALBERTA\*

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A suite of apatite minerals has been identified in subsurface formations covering many townships of the Alberta Basin. Mineralization occurs at depth in phosphorite deposits which are also producing petroleum and natural gas reservoirs. Several bench scale projects were conducted in the United States and Canada in the 1980s. Tests included:

- (1) Leaching experiments of crushed ore samples under ambient and simulated reservoir conditions, and
- (2) Flow-leaching experiments of core plugs from a deep well.

Positive results preceded a successful in situ recovery phosphatic solutions from a test well drilled, unsuccessfully, for oil from the phosphorite zone. Technical and economic feasibility studies are in progress supported by the Canadian Federal and Alberta Governments' new Partnership Agreement over a three year program. Phases II and III will include demonstration in situ pilot projects and commercial development. Canada is now totally dependent on imported phosphate rock supplies as feedstock for a large domestic fertilizer manufacturing industry. The success of this project will be of significant economic and environmental benefit to Alberta and Canada.

## **GEOLOGY, AND PROCESSING FACILITY, CALMAT CO. RELIANCE PLANT, IRWINDALE, CALIFORNIA**

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CalMat Co. is one of the largest producers of construction aggregates in the United States. The CalMat Reliance plant is located in Irwindale, California, and is situated on an alluvial fan formed by the San Gabriel River. The fan deposits are of Holocene age and were derived from granitic and metamorphic bedrock exposed in the San Gabriel Mountains to the north. The sediments are poorly sorted and range in size from large boulders to clay size particles. The coarse material is hard and durable and consists of quartz diorite, granodiorite, granitic gneiss, schist and minor amounts of volcanic rock. The matrix is comprised of silty sand with varying amounts of clay. Thin silt and clay lenses occur sporadically throughout the deposit. The clay content of the matrix and the degree of weathering of the coarse material increase with depth. Based on seismic data, the alluvial fan varies from 200 to 400 feet thick and overlies crystalline bedrock.

The Reliance plant was constructed in 1971 and 1972. It has a nominal capacity of 1,400 tons per hour, and typically produces more than three million tons of aggregate products per year. Alluvial fan sediments are mined from a gravel pit situated adjacent to the plant. The material is fed through a mobile 48-by-60 inch, in-pit jaw crusher, then transported by conveyor to the main plant to be processed. The plant is modern and highly efficient. It has a typical wet and dry circuit and is capable of producing a wide range of aggregate products.

To extend the life of the plant, a 9,000 foot conveyor system is being constructed to connect the plant to a granite quarry located north of Irwindale. CalMat Co. owns 50 percent of the granite quarry, and will use the conveyor to export several million tons of crushed rock to Reliance each year. The existing plant will be modified to process the crushed rock.

## **FORUM '94, 30TH FORUM ON THE GEOLOGY OF INDUSTRIAL MINERALS—A MARITIME CANADIAN EXPERIENCE**

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Forum '94 is to be held May 21th to 27th and will consist of a pre-meeting field trip in New Brunswick, technical sessions in Halifax, Nova Scotia and a post-meeting field trip in Nova Scotia. Although slightly longer in format than previous Forums, this arrangement will allow participants to take in very interesting field trips covering both host provinces.

Field trip highlights include visits to the world's largest gypsum mine, a zero effluent 2.0 million tpa potash mine, a Fuller-Beckenbach annular-shaft lime kiln, and an operating tidewater export aggregate operation. Parallel guest trips will allow visitors to enjoy great Maritime hospitality, plenty of fresh seafood delights, and local history and culture. Two days of technical sessions will be held in Halifax at the well appointed World Trade and Convention Centre which is located in the heart of downtown. It is also connected by tunnel to the Prince George Hotel, site of our welcoming reception and final banquet.

Plans are well underway for next year's forum. Maritime hospitality combined with excellent technical sessions and field trips are guaranteed to entertain and enlighten one and all.

## **MITSUBISHI'S CEMENT OPERATIONS LUCERNE VALLEY, CALIFORNIA**

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No abstract submitted.

## **GEOCHEMICAL AND GEOPHYSICAL SURVEYS IN TI-HF-REE-TH-U PLACER EXPLORATION\***

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Selected elements from the Hydrogeochemical Stream Sediment Reconnaissance (HSSR) data base of the National Uranium Resource Evaluation (NURE) program are diagnostic and may predict the presence of ilmenite, rutile, zircon, and monazite in samples from the east-central Coastal Plain province and the Pacific Northwest area of the United States. The hypothesis of this study is that anomalous concentrations of elements such as Ti and Hf in stream-sediment samples indicate the probable presence of common economic heavy minerals such as ilmenite and rutile in the case of Ti, zircon in the case of Hf, and monazite in the case of REE (rare earth elements). Zr was not always analyzed in HSSR, particularly for samples from the northwestern United States. The REE are commonly associated with Th and with U in heavy minerals such as monazite. Ilmenite and rutile are the most common Ti-bearing minerals in Cretaceous and younger sediments. Because Zr and Hf possess extraordinary geochemical affinity, enrichment in Hf usually indicates the presence of zircon.

The geochemical signature of known deposits of heavy minerals has been determined and is recognized over a large portion of the Coastal Plain of Virginia, North Carolina, South Carolina, and Georgia and in the western United States. The Fall Zone region (generally coincident with exposures of Cretaceous and Tertiary rocks and sediments) in Virginia, North Carolina, South Carolina, and Georgia shows a continuation of this geochemical pattern. This pattern is closely approximated by the NURE spectral aeroradiometric data. In the northwestern United States, Ti-Hf (or Zr)-REE-U-Th anomalies occur in Cretaceous and Tertiary continental sedimentary rocks, in Quaternary valley-fill deposits, in Cretaceous and Miocene volcanic rocks (and adjacent valley fills), in Mississippian marine deposits, in Precambrian metamorphic rocks, and in Quaternary outwash and terrace deposits.

Extensive areas, particularly in the largely unexplored Central Plains, may also have exploration potential for the ilmenite-zircon-monazite mineral suite and could be studied in a similar manner. The results of this study suggest that the potential for Ti-Hf-REE-U-Th-bearing deposits of placer heavy-mineral suites in surficially exposed sediments and sedimentary rocks in the United States may be much greater than previously thought.



## MÉXICO—MARKETS AND OPPORTUNITIES FOR INDUSTRIAL MINERALS

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México has long been known as a treasure house of minerals, both metallic and nonmetallic. The development of these minerals has been somewhat delayed by political, financial, and transportation factors. This situation is in a process of change that has again focused attention on México. For example, the Salinas de Gortari administration has undertaken a series of measures designed to help the Mexican mining industry from the standpoint of legislative, fiscal, and administration procedures. This paper takes a look at the potential for industrial mineral opportunities in the "new" México.

There is a significant domestic Mexican market for numerous industrial minerals. Because of México's geographic location, the United States of America also represents a market for its nonmetallics. Conversely, México is the destination for significant quantities of industrial minerals from the U.S.A. Emerging domestic markets and export opportunities indicate a bright future for industrial mineral markets. Favorable transportation, political and financial factors are expected to greatly increase this mutual commercial relationship in the future.

## WOLLASTONITE IN QUÉBEC PROVINCE, CANADA\*

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The Grenville structural province, a 400 km-wide belt of Precambrian metamorphic rocks which crosses the province of Québec in a northeasterly direction, is the host of several wollastonite occurrences. Most of these are found in marble and calc-silicate rocks enclosed within or located near intrusive bodies. Reconnaissance and detailed mapping of such zones have helped to identify areas of interest for wollastonite exploration.

The most important zone is located in the huge Lake Saint-Jean anorthosite massif in the central part of the Grenville. A recent geological mapping project has revealed the presence of wollastonite in metasedimentary roof pendants. The main occurrence consists of diopside and wollastonite in a zone at least 3 km long and 150 m wide. Preliminary sampling suggests an average grade of 50% wollastonite with an aspect ratio of 15:1.

Other wollastonite deposits occur in the western part of the Grenville, mainly north and west of Montréal, where the Morin anorthositic complex and a large syenite mass intrude the metasedimentary rocks of the Grenville Supergroup. Marble bands with up to 85% wollastonite occur locally at the southern margin of the complex.

Significant wollastonite occurrences have recently been found in the eastern part of the Grenville. One of them is located in metamorphosed calcareous rocks which are part of the granulite facies Manicouagan metamorphic complex. A representative sample analyzed 54% wollastonite. Farther south, an inclusion of diopside-wollastonite gneiss containing an estimated 40% wollastonite occurs at the margin of the Pentecote River anorthositic complex.

# CHARACTERIZATION OF KAOLIN RESOURCES IN MINNESOTA\*

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Minnesota has large kaolin resources located throughout the state. Currently, the resource is only being exploited in the south-central region of the state for use in bricks and portland cement. Past work in Minnesota has focused on defining the resources and occurrences of the various kaolin grades in the central region and specifically, in the areas of current mining. Current work is focused on an assessment of the occurrences of kaolin in northern Minnesota, using information and samples from the Minnesota Department of Natural Resources (MDNR) Drill Core Library located in Hibbing, Minnesota.

Kaolin occurs in three varieties: 1) residual (primary) deposits formed during pre-Late Cretaceous weathering of various bedrock type; 2) reworked (secondary), sedimentary deposits formed from the residual deposits in a terrestrial fluvio-lacustrine environment; and 3) Late Cretaceous sediments which are organic-rich lacustrine, paludal, and marine in origin. All of these units were modified by Pleistocene glaciation and may be partially or completely removed from some areas of the state. Each of the three occurrences has distinct properties and are currently being mined in south-central Minnesota for use in the portland cement and brick industries.

The residual deposits in south-central Minnesota are currently used by the portland cement industry in Iowa. These deposits, weathered from the Morton Gneiss, are 10 to 75 m thick and consist of kaolinite (25% to 80%) and quartz (10% to 30%) as the major minerals, with minor to trace amounts of illite, chlorite, feldspar, mica, and iron oxides present. As expected, the grade of the material decreases with depth. The kaolinite from these deposits is not well ordered and has a wide range of particle size. Residual deposits formed on other rock types, i.e., granites, and felsic sediments, tend to have well ordered kaolinite and a narrower range of particle sizes. Examples of these residual deposits are found formed on the Fort Ridgely Granite in south-central Minnesota.

Reworked sedimentary deposits are currently used in the brick industry. These sediments overlie the residual deposits and consist of pisolitic kaolinite, shale, siltstone, and sandstone, with conglomerates. The sequence is typically fining upward from basal sandstones into shales, commonly capped by pisolitic kaolinite. This sequence may be repeated one or more times in an occurrence. Geologic mapping in south-central Minnesota has illustrated the fluvial nature of these deposits. The reworked package of sediments is commonly 2 to 10 m thick, but may reach a thickness of 20 + m in some areas. Drill hole information indicates there are several of these occurrences in central and northern Minnesota, which are thought to be lacustrine sediments. The kaolinite in the reworked sediments is well ordered and has a narrow range of particle size in individual units. The shale, siltstone, and sandstones are dominantly composed of kaolinite and quartz, with minor to trace illite and iron and titanium oxides. The pisolitic caps are kaolinitic, with trace amounts of gibbsite and quartz. Iron oxides in the pisolitic caps can be minor to major in abundance and decrease with depth.

Late Cretaceous sediments, which overlie the residual and reworked kaolins, formed during the transgression of the Western Interior Seaway and are currently used in the brick industry. The sediments are composed of shales, siltstones, sandstones, and lignites, which occur in fining upward sequences. The Late Cretaceous sediment package ranges from 2 to 100 m in thickness. Typically, these are freshwater sediments, but marine examples occur in northern and western Minnesota. Mineralogically, they are composed of well-ordered kaolinite and quartz, with minor to trace illite, chlorite, gypsum, and carbonized material. Carbonate is present in many of the marine sediments but absent in the freshwater material. Many of the shale units are red firing ball clays and typically are 1 to 3 m thick. Drill hole information from northern Minnesota indicates there are thicker deposits of these ball clays preserved under the glacial overburden.

# GLOBAL DEPLETION AND DEMAND OF BIOESSENTIAL AGROMINERALS—PHOSPHATE ROCK AS AN EXAMPLE AND ITS IMPACT ON GLOBAL FOOD SUPPLY\*

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*"A warning about the future should not be taken as prediction of doom, but rather as a mandate to follow a different path."*

—paraphrased from: *Beyond the limits* (1992)

An essential and indisputable link exists between phosphate rock and world food supply. Phosphorus is required for all life. Phosphate rock is the source of phosphorus used to make phosphatic fertilizers, which are essential for growth of the food needed by humans in the world today and the future.

We modeled the depletion of the known reserves and reserve base of phosphate rock based on various scenarios for increasing population and future demand for phosphate. Using these scenarios, the presently known reserves will be depleted within the next 100 years. World reserves and the reserve base (which includes reserves) of phosphate rock are currently inventoried as 12.5 and 33.8 gigatons (Gt), respectively. For this model, we used rates of growth of demand for phosphate rock of between 1 and 1.7 percent annually. These demand growth rates are possibly conservative—forecasts of demand growth exist that use higher rates. Growth rates of two to three percent markedly shorten the time of depletion.

We also examined demand rates that decrease over time toward demand stasis. Growth-rate scenarios that stabilize demand at the year 2100 are little different from unconstrained growth scenarios because much of the phosphate reserve base will have been depleted by the time significant demand reduction occurs. Alternatively, demand stabilization by 2025 extends the reserve base by only about 50 years. For conservative annual demand increases just over one percent, the introduction into the reserve base of 20 Gt of new resources, which is equivalent to present world inferred resources, extends the time of depletion until about 2135; however, if annual demand increase by three percent, which still is slightly under the average rate of demand growth for the world during the past three decades, the addition of inferred reserves extends the depletion date until only 2083.

The combination of reduced demand coupled with the addition of a new, larger reserve base produces a cumulative extension of the time to depletion. Several additional considerations could affect these depletion scenarios and cause those scenarios to be substantially too high or too low. Nonetheless, the ineluctable conclusion in a world of continuing phosphate demand is that society, in order to extend phosphate rock reserves and reserve base beyond the 100 year depletion date, must find additional reserves and reserves and/or reduce the rate of growth of phosphate demand in the future. Society must either (1) increase the efficiency of use of known resources of easily minable phosphate rock; (2) discover new, economically-minable resources; or (3) develop the technology to economically mine the vast but currently uneconomic resources of phosphate rock that exists in the world. Otherwise, the future availability of present-cost phosphate, and the cost of availability of world food will be compromised, perhaps substantially.

## P.W. GILLIBRAND'S AGGREGATE AND ILMENITE OPERATIONS SOLEDAD, CALIFORNIA

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# HOW GEOLOGIC REINTERPRETATION AND NEW RECOVERY METHODS REPEATEDLY EXPANDED THE MINERAL RESERVES AND MINING LIFE OF THE SEARLES LAKE EVAPORITE DEPOSIT SAN BERNARDINO COUNTY, CALIFORNIA

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The Searles Lake evaporite deposit is one of the world's largest chemical mineral sources—over \$2 billion in mineral values have been recovered to date. Most of these values have been recovered from brines occurring in a number of separate salt mineral layers within the upper 600 feet of the stratigraphic section. The Searles Lake deposit is a thick playa lake sedimentary accumulation approaching 3,000 feet in thickness and was deposited in Searles Valley during Pleistocene time. Searles Lake was the last in a chain of fresh water lakes located east of the Sierra Nevada Range. During its highest level, the lake level was as much as 600 feet above the present lake floor.

In descending order, the principal brine-filled salt units include the Upper Structure, Lower Structure, and Mixed Layer. The solid salts represent periods when the lake was either shallow or a "dry" playa, while the interbedded highly carbonaceous muds represent periods when it was fuller and less saline and alkaline. The solid phase minerals now present in the saline layers were not all those precipitated during original deposition, as some are definitely diagenetic and most of the minerals are recrystallized.

The history of mineral production from the Searles Lake playa is one of continually expanding reserves and opportunity due to periodic reinterpretation of the geology and introduction of new recovery technologies. "Borax" Smith originally discovered borax on the surface of the playa in 1878, and operated a plant thereon for years. In 1912 potash was discovered in the brines, inspiring development of a complex evaporation recovery scheme and construction of a plant by the newly formed American Trona Company in 1923, tapping the Upper Structure salt through a series of brine wells on the playa salt center. By 1932 brine grades began to drop precipitously and—following geologic and engineering reinterpretation—additional marginal lands of the playa were tied up and a massive new drilling and development program successfully conducted to increase the high-quality brine reserves and the plant headfeed. By 1947, the Lower Structure salt unit was discovered with its seven salt layers, each having distinct brine compositions. These brines were used to supply a new carbonation plant recovering soda ash and borax.

By 1961, brine grades again began a disturbing drop, and American Potash & Chemical Corporation brought in a new geologic team to again redefine the reserves and develop new drilling and recovery approaches. This program was successful, and in 1965 also led to drilling of several holes that discovered the deep high-carbonate brines now used by the operators. Kerr McGee Corporation acquired the venture in 1967, and introduced many oil field drilling and production techniques that again greatly expanded the deep trona-bicarbonate solid and brines reserves of the Mixed Layer. The large Argus soda ash plant was completed in 1972, utilizing these deep brines. Solution mining techniques were also introduced to bring the solid phase trona values into solution, where they could be recovered. Solar pond use to upgrade Upper Structure brines was also greatly expanded to improve the slowly falling brine grade from that source.

Stauffer Chemical also operated a carbonation plant on the south end of the Lake, and Kerr McGee acquired this operation as well in 1972. U.S. Borax, Kerr McGee, and several early operators have also recovered solid trona and/or salt by surface scrapping and by dredging of the Upper Structure. Attempts in the 1920s and 1970s by other companies to separate and recover the evaporite minerals completely by solar evaporation pans failed. North American Chemical Corporation currently operates the venture.

# THE MUD HILLS CLINOPTILOLITE DEPOSIT AS A SOURCE OF ION EXCHANGE MATERIALS FOR NUCLEAR WASTE TREATMENT\*

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The Mud Hills clinoptilolite deposit is located in the Mud Hills, about eight miles north of Barstow, San Bernardino County, California. It comprises a portion of a zeolitized silicic ash-fall tuff unit, informally named the "Skyline Tuff," occurring within the Miocene Barstow Formation. This formation consists of tuffaceous shale, mudstone, bentonite, sandstone, conglomerate, and zeolitized air-fall tuff, and reworked tuff. The Skyline Tuff locally averages 10 feet in thickness, dips 10-14° south, and is exposed in outcrop sufficiently to allow extensive open-pit mining of the site. Numerous other thinner zeolitized tuff beds in the formation offer no economic potential.

Occidental Minerals Corporation explored and developed the Mud Hills deposit during 1978-1981, then conducted a very selective mining program during 1982 to supply British Nuclear Fuels Ltd. (BNFL) with several thousand tons of carefully mined, screened product. Development work performed prior to mining included core-drilling on 10.6 meter centers with one-foot sampling intervals to determine the Sr/Cs retention level, together with the determination of zeolite mineral content, ammonia cation exchange capacity, wet abrasiveness, and other physical properties which might affect the material performance. The mining and processing specifications were very strict, but the material was on geologic maps and cross-sections, close-center drill hole and test data, frequent surveying, and constant site observation by OxyMin and BNFL inspectors during the excavation phase.

This material is now in use at the BNFL nuclear fuel reprocessing plant ion exchange site (SIXEP) near Sellafield, England. Spent liquid wastes with a high charge of radioactive cesium and strontium are passed through ion exchange columns filled with screened clinoptilolite, successfully removing over 98% of the  $\text{Sr}^{90}$  and  $\text{Cs}^{137}$ . The SIXEP plant waste stream is released into the Irish Sea. Prior to the successful operation of the SIXEP plant, such release created radioactive contamination in the Sea and along the Low Countries coastline. After several years of operation, the Mud Hills product has performed well, exceeding the design expectation in terms of discharge reduction.

## INDUSTRIAL MINERALS IN BRITISH COLUMBIA—AN OVERVIEW\*

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The value of industrial minerals produced annually in British Columbia is over \$400 million. B.C. is a major source of limestone for the Pacific northwest and 4.5 million tonnes are shipped from Texada Island annually to destinations along the coast from Alaska to northern California. Also, 500,000 tonnes of gypsum produced in the southeast corner of the province are processed mostly in Alberta and British Columbia. B.C. magnesite, diatomaceous earth, pyrophyllite and refractory clays are locally processed into high-value products. Together with co-product sulphur, they are successfully marketed around the globe.

The province also produces a variety of commodities including barite, dolomite and calcium carbonate fillers, silica, magnetite and small quantities of rhodonite and jade. Recent additions to the industrial minerals industry include a producer of fuller's earth (industrial and domestic absorbent) and a manufacturer of granite tile.

B.C. industrial minerals development opportunities include peat, talc, asbestos, perlite, residual kaolin, abrasive garnet. REE and yttrium, niobium, nepheline syenite and synthetic minerals like silicon carbide, mullite or spinel.

## BARITE MINERALIZATION, ALTERATION AND GEOCHEMISTRY OF THE WATERMAN MINE, SAN BERNARDINO COUNTY, CALIFORNIA\*

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The Waterman Hills are comprised of a basement core complex of Waterman Gneiss and Mesozoic intrusive rocks overlain by Tertiary Pickhandle Volcanics and sedimentary beds of the Barstow (?) Formation. The Waterman Hills Detachment Fault (WHDF) forms the contact between the footwall basement complex and the hanging wall Tertiary rocks.

In the Waterman Mine area barite mineralization is hosted by the Miocene Pickhandle Formation. The most important units are a poorly indurated volcanic debris flow and a massive dacitic tuff. Barite-silver mining has been confined to a steeply, west-dipping vein which roughly follows the contact between these units. Mapping at a scale of 1:3600 reveals, however, that the vein locally crosscuts the contact. The vein strikes nearly north-south for 300 meters then turns to the northwest for approximately 160 meters. The change in strike of the vein coincides with the development of a slickensided footwall suggesting mineralization along the northern portion of the vein has been localized within a northwest-trending fault zone.

Mineralization consists largely of comb-structured, tabular barite crystals often exceeding two centimeters in length. Fine-grained massive barite replaces volcanic clasts and permeable horizons within the volcanic sequence. Native silver, cerargyrite, pyrite and argentite have been noted. Alteration consists of massive-bedded jasperoid which pre-dates ore emplacement. Silicification, including minor opal and chalcedony, argillic alteration (kaolinite – dickite) and propylitic alteration (chlorite – epidote – calcite) are closely related to ore deposition. The barite mineralization has undergone extensive brecciation and localized supergene alteration. This alteration includes secondary silicification and the formation of iron-oxides. Fluid inclusion geothermometry indicates the barite was deposited at temperatures of 170°C to 210°C.

The following sequence of events best explains the Waterman Hills deposit: 1) barite-silver bearing fluids circulated along the WHDF, 2) the fluids were heated by underlying plutons and driven convectively upward along a listric fault in the Tertiary volcanic rocks, and 3) as the fluids cooled ore deposition occurred within the high angle fault zone and permeable horizons of the host volcanics.

## DIAMONDS IN CANADA: AN OVERVIEW OF CURRENT DEVELOPMENTS

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Exploration activity for diamonds in Canada has recently experienced a dramatic increase. Disclosure of a diamond discovery exhibiting all of the features of a world-class kimberlite province in the Lac de Gras area of Canada's Northwest Territories has sparked substantial interest in Canada and abroad, and has triggered the largest staking rush in the history of Canadian exploration.

In this paper, we will report on the nature and extent of current exploration activity in Canada, with special attention to long-term prospects for potential Canadian diamond producers in the context of world markets.



# GEOLOGY, MINING AND PROCESSING OF ALBERHILL DISTRICT SEDIMENTARY FIRECLAYS AND RESIDUAL CLAY AND SHALES

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A significant deposit of refractory fireclays, residual shales and clays has been mined at this site for over 100 years. The deposit has been exposed over an aggregate area of approximately 3,000 acres, and to a depth of approximately 100 feet. Clays from this deposit have furnished a full range of structural ceramic products to the western United States and markets beyond. Aggregate materials and high-alumina clay for the Portland Cement Industry are also developed. Quality building products for the construction and contracting industries as well as mineral-based employment for Californians have made this a consistent industrial mineral property.

In this paper, exploration, ceramic testing and production methods will be discussed. The clay deposits occur in the Paleocene Martinez Formation occupying a down-dropped synclinal faulted block (graben) situated between the Glen Ivy Fault on the southwest and Jurassic igneous rocks of the Perris Block on the northeast.

The deposition and development of the economic clays are represented by the following sequence; 1) deep residual weathering of Triassic Bedford Canyon Slate and Santiago Peak Volcanics, 2) deposition of kaolin-rich sedimentary fireclays and 3) deposition of chlorite-rich arkosic sands and clays (montmorillonite and saponite). The entire sequence is overlain by Quaternary fanglomerate and terrace deposits.

## LIMESTONES OF NEW MEXICO AND ADJOINING AREAS SUITABLE FOR SULFUR REMOVAL IN COAL-FIRED POWER PLANTS\*

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Widespread high-calcium (HC) limestones that occur in New Mexico and adjoining areas are low in magnesium, but some units include shale interbeds that would be deleterious for sulfur removal usage. In southwest New Mexico, limestones in the thick Mississippian Escabrosa, Pennsylvanian-Permian Horquilla, and Cretaceous U-Bar units are HC as are strata in the Mississippian Lake Valley, Pennsylvanian formations, Permian Hueco, and parts of the Permian Capitan Limestone of south-central and southeast New Mexico and west Texas.

In north-central and central New Mexico, many limestones in the Pennsylvanian Madera Formation are HC as are some of the Cenozoic travertines. In northwest New Mexico, where the present-day mine-mouth coal-fired power plants occur, there are no HC limestones, but to the north in southwest Colorado some beds of the Mississippian Leadville Limestone and Pennsylvanian Hermosa Formation are HC.

## REMOTE SENSING AND GEOPHYSICAL TECHNIQUES FOR LOCATING AND ASSESSING POTENTIAL SOURCES OF AGGREGATE\*

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Crushed stone and sand and gravel are the two main types of natural aggregates, and together amount to about half of the non-fuel mining volume in the United States. With the increasing need to rebuild the nation's highway infrastructure, growing environmental concerns, and continued loss of available land to urban development and other uses, new sources of aggregate need to be located and set aside for future use. The identification of areas of potential aggregate resources is the first step toward assuring adequate supplies. However, existing surficial geologic maps may not be available for areas of interest, and surficial geologic mapping using conventional interpretation of black-and-white aerial photographs is likely to be costly and time consuming.

The U. S. Geological Survey has recently initiated a project to identify and demonstrate remote sensing and geophysical techniques, dependent on specific terrain and climatic parameters, that can effectively locate and assess sand and gravel and sources of bedrock suitable for use as crushed stone.

The United States will be divided into study areas defined by factors such as origin and distribution of aggregates, and climate and vegetation. Characteristics of representative types of known aggregate deposits, such as surface texture, mineralogy, soil moisture, and vegetation, will be compiled with the goal of identifying those physical properties (spectral reflectance, thermal properties, resistivity, etc.) that can be detected and mapped with remote sensing and geophysical techniques. The applicability of a variety of airborne and spaceborne remote sensing techniques, including multispectral reflectance, thermal data, and side-looking radar, will be evaluated for areas of known aggregate deposits that have been thoroughly studied by standard methods. Geophysical techniques, especially airborne resistivity measurements (VLF), will be evaluated for the same areas to determine their potential usefulness in locating aggregate resources. Selected sites will be examined with ground-based resistivity equipment to fully develop the methodology for rapidly determining the extent of potential aggregate deposits.

## **MINERAL LAND CLASSIFICATION IN CALIFORNIA\*\***

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One of the principal responsibilities of the California State Geologist is to provide local governments with maps and information regarding mineral resource occurrences within their jurisdiction. The primary objective of this effort is to furnish basic data that is essential in planning for and accommodating wise development of mineral deposits that are important to the economic well being of the region, state, and nation. Local government agencies are required by law to incorporate the information provided by the State Geologist into their general plans and formulate mineral resource management policies that emphasize conservation and development of mineral deposits.

The Mineral Land Classification program was initiated by the State Geologist in 1977 under authority of the California Surface Mining and Reclamation Act (SMARA). To date, about 33,000 square miles of land have been classified for mineral resource potential. Most of the mineral land mapping has been conducted in three principal areas: 1) metropolitan areas of the state, where urban encroachment has greatly diminished available supplies of construction aggregate; 2) Sierra Nevada foothills, a region that is undergoing dramatic population increases; and 3) the Mojave Desert and Great Basin regions, where large Federal land withdrawals are pending that could preclude mining.

Mineral land classification studies address the overall mineral potential of a region through the identification of local and regional geologic factors that control or influence the formation of mineral deposits. These studies are field-intensive surveys that enable project geologists to gain first-hand knowledge about the nature and distribution of mineral deposits in a given area and portray that information accurately in map form.

This paper summarizes the progress made in the Mineral Land Classification program in the metropolitan, Sierra Nevada foothills, and the Mojave Desert/Great Basin regions of California. Selected projects from each area are discussed in detail.

## **CALIFORNIA INDUSTRIAL MINERALS—A POTENTIAL SOURCE OF VALUABLE COMMODITIES\***

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The Bureau of Mines, as part of an effort to maximize minerals and metals recovery from domestic sources, has investigated the feasibility of recovering heavy minerals as byproducts from sand and gravel, placer gold, and other industrial mineral operations in California. Heavy mineral (black sands) concentrates were prepared from sands sampled from 110 locations. Magnetite, ilmenite, zircon, chromite, radioactive minerals, platinum-group minerals, and gold were identified in many of the concentrates. Beneficiation studies were performed on these concentrates to recover individual mineral products. Gold was recovered by amalgamation; platinum-group metals and radioactive minerals by flotation; magnetite, ilmenite, zircon, chromite by magnetic and high tension separation techniques.



# MINERAL AND ENERGY RESOURCES IN THE SALTON TROUGH, CALIFORNIA

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The Salton Trough of California is an active continental rift, the landward extension of the divergent tectonics of the Gulf of California and the East Pacific Rise spreading center system. Shallow magmatic heat sources, thick porous deltaic sediments, tectonic activity and a persistent saline lake environment have interacted to yield a variety of Pleistocene to modern hydrothermal systems. The Trough contains large known reserves of geothermal, metallic and industrial mineral resources, but high potential for additional resource discovery exists along its margins and southward into Baja California.

Along the east margin of the Trough there occur disseminated epithermal Au deposits such as Mesquite, one of California's largest Au mines. Formed at the latest during the Oligocene in dilatant shear zones generated by strike-slip faulting, its location reflects a proto-rift strike-slip tectonic environment as well as the presence of Jurassic source rocks.

The oldest known non-metallic deposit in the Trough, the Fish Creek gypsum deposit, occurs along the west margin of the Trough. It was formed by a late Miocene seawater incursion into a rapidly subsiding embayment within the proto rift. This deposit supplies the largest gypsum mine in the U.S. Small occurrences of younger Na and Mg sulfate deposits, possibly hot-spring related, occur on the east side of the Trough along the modern San Andreas fault.

Four to five million years ago the Colorado River delta prograded transaxially across the Trough, influencing the character of Pliocene and younger sedimentation and hydrothermal activity. The northern part of the Trough became a closed basin, filled intermittently by large freshwater lakes. Along the west margin of the rift lies the Modoc hot spring gold deposit, a shallow stockwork silica vein system overlain by sinter terraces and acid sulfate alteration. This deposit occurs at the intersection of a range-front growth fault with fossil lake levels, suggesting possible paleohydrologic control by ancient lakes.

Modern geothermal systems within the Trough include low-T (<250°C) systems, such as Heber and East Mesa, localized along high-angle faults where shallow groundwaters are conductively heated above basement highs. These blind systems have no surface expression and only moderate geophysical anomalies. Some are siliceous and gold-bearing, perhaps modern analogs for Modoc whose fluids have not yet seen the surface.

High-T (>250°C) active systems occur in sediment filled pull-apart basins developed over spreading center fragments (for example the Salton Sea, Brawley, and Cerro Prieto). These systems exhibit high heat flow, strong gravity and magnetic anomalies, and often have surface manifestations such as Quaternary volcanoes and thermal features. Many contain hot metalliferous brines that have evolved in the saline lake environment of the northern Trough. The brines rise diapirically to depths of only 0.5 km as they are heated by the underlying MORB igneous activity. Their tectonic setting and evolution may be good analogs for the genesis of ancient stratiform base metal deposits in continental rift settings.

The potential mineral reserves of the Salton Sea geothermal brines are enormous. More than  $10^{13}$  kg of hot brine are present, estimated to contain:

Fe	18 million tonnes	Li	2 million tonnes
Mn	17 million tonnes	Pb	1 million tonnes
Zn	6 million tonnes	Ag	350 million ounces
Sr	4 million tonnes	Pd	350,000 ounces

Extraction and separation of these elements presents a formidable technological challenge.

## GEOLOGY AN MINING OF IDAHO PHOSPHATE\*

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Idaho contains the thickest and richest phosphate deposits in the western U.S. and is ranked third nationally in the production of marketable phosphate. Phosphate rock in southeastern Idaho is processed into either: (1) phosphoric acid, for production of chemical fertilizers essential for the crops, or (2) elemental phosphorus, for a wide variety of chemical products.

Phosphate rock contributes significantly to Idaho's economy and is currently the number one mineral commodity in terms of value in the state, ahead of silver, molybdenum, zinc, and gold. In 1992, almost 6 million tons of phosphate were produced from six phosphate mines on Federal lands in southeastern Idaho. Since phosphate is a leasable mineral, royalties resulting from phosphate production are of direct benefit to federal, state, and county governments.

Phosphate resources are located within the Meade Peak Phosphatic Shale Member of the Permian Phosphoria Formation. The Phosphoria Formation consists mostly of chert, carbonaceous and phosphatic mudstone, and phosphorite. The Phosphoria is centered in southeastern Idaho, but extends into adjacent states of Montana, Wyoming, Utah, and Nevada.

During Paleozoic and Mesozoic time, over 100,000 ft of sediments were deposited in the region and now occupied by southeastern Idaho and western Wyoming. The Meade Peak was deposited in shallow waters of an epicontinental foreland basin between the Antler Orogenic Belt and the North American Craton during Early Permian time. Late Jurassic through Cretaceous eastward-directed compressional tectonics resulted in substantial crustal shortening. Crustal shortening, achieved by regional folding and thrust faulting resulted in the effective doubling of over 100,000 feet of Paleozoic and Mesozoic sedimentary rocks in the region. Tertiary through Quaternary regional extension superimposed an overprint of north- and northwest-trending normal faults on the already complex structure. Post-depositional alteration (or weathering), related to depth and faulting, has removed calcite, dolomite, and organic material by solution and oxidation from parts of the Meade Peak. The resulting relative enrichment of phosphate content is conducive to economic mining of phosphate rock by open-pit methods.

The Phosphoria Formation is exposed along the flanks of north-trending regional folds. Bedding typically dips from 20° to 60° and may be vertical to overturned. Open-pit mines follow the north-trending strike of the Meade Peak. Pits are elongate and may range up to several miles in overall length. Economic recovery of phosphate is limited by grade (%P<sub>2</sub>O<sub>5</sub>), thickness, stripping ratio, an extent of alteration and structural complexity. Other chemical criteria that affect suitability for processing include content of MgO, CaO, Fe<sub>2</sub>O<sub>3</sub>, Al<sub>2</sub>O<sub>3</sub>, and organic constituents.

Modern selective mining techniques, recent innovations in processing technology and reclamation hold significant promise for optimizing recovery of phosphate as well as addressing environmental concerns for prudent mining in southeastern Idaho.

## THE GEOLOGY AND ECONOMIC DEVELOPMENT OF SEARLES LAKE\*

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Searles Valley is located approximately 200 km northeast of Los Angeles in the Basin and Range province and occupies the lowest part of the basin is Searles Dry Lake Playa, which is about 10 km east to west and 16 km north to south. Three major subsurface evaporite horizons have been identified and are termed from bottom to top, the Mixed Layer, Lower Salt, and Upper Salt. The evaporite beds were formed by desiccation of runoff from the eastern Sierra Nevada range during Quaternary time. The saline beds are generally brine saturated with the important ions being sodium, potassium, carbonate, bicarbonate, sulfate, chloride, and borate. These ions are present in the brines in various concentrations and have combined to form the minerals halite, hanksite, trona, nahcolite, burkeite, borax, thenardite, sulfohalite, glaserite, and others. North American Chemical Company selectively pumps the interstitial brines to feed their chemical plants located on the western edge of Searles Lake. Minerals have been mined since 1873, beginning with borax and raw trona scraped from the surface. Brine processing began in 1914 with potassium chloride and borax recovery. Expansions have added sodium sulfate and soda ash to the product mix. Currently, dredging of trona ore is also taking place.

## RECLAMATION COMPLIANCE IN CALIFORNIA

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Goals of the California Surface Mining and Reclamation Act (SMARA) include assuring that no mine is operating in the state without a reclamation plan, that all reclamation plans include minimum, verifiable statewide standards, and that reclamation is achieved. The Office of Mine Reporting and Reclamation Compliance, within the Resources Agency's Department of Conservation, is the primary monitoring and enforcement arm for mined-land reclamation and reporting compliance. Among its duties, are the following:

Create and maintain a database on all mines in the state. This data, based on reports submitted annually by mine operators and verified by Office staff, are available to the public, to miners, and to public agencies, for purposes of information or regulation. Verification of mines operating without permits and/or reclamation plans, and identification of nonreporting mines accompanies this task.

As the enforcement and regulatory backstop for local governments, the Office assures that SMARA is carried out correctly in the state. Office staff audit local government mine inspections, investigate complaints against miners, issue citations to violators of SMARA, and assist local governments in their mine regulation efforts. Responding to situations creating health, safety, and/or environmental problems accompanies this task.

In cases where the State Mining and Geology Board takes over as the SMARA lead agency in a jurisdiction, Office staff perform inspections, process reclamation plan applications, and handle routine staff duties related to SMARA compliance.

Before 1995, submit to the Governor and Legislature a report which evaluates the effectiveness of SMARA.

## CAN LOCAL DEVELOPMENT OF INDUSTRIAL MINERALS UNDER THE RESTRAINT OF MORE ENVIRONMENTAL REGULATION, COMPETE IN THE NEW INTERNATIONAL MARKET?

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Environmental protection is costing industry money. In these times of fierce competition with international markets, the environmental movement will create future economic hardships for the industrialized nations. The only solution to fair competitiveness is international environmental protection laws and regulations. Not only will such laws and regulations protect present economic balances, they will take environmental protection to a global level. According to our environmentalist friends, time is running out to stop a global disaster. Industry cannot change the habits of civilizations who constantly strive for a better way of life, only an enforceable global controlled plan can govern future orderly world development.



# BRINE MINERAL OCCURRENCE IN THE DIABLO MOUNTAIN (BLM) STUDY AREA, AND ITS POSSIBLE SIGNIFICANCE TO PACIFIC RIM TRADE\*

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In 1988, at the request of the U.S. Bureau of Land Management, the U.S. Bureau of Mines conducted a mineral investigation of the 34,310-acre Diablo Mountain (Additional) study area (OR-001-058), Lake County, Oregon, about 45 miles northwest of Lakeview.

Geologically, the study area is in a region of fault block-formed mountains and basins characterized by interior drainage, and lies along the east shore of saline Summer Lake. The area is mainly underlain by unconsolidated Quaternary and Pleistocene lake and playa sediments, which may include subsurface evaporite mineral deposits and resources.

No mineral resources have been identified, but brines within the sediments, sampled from shallow auger holes, host occurrences of sub- and marginally-economic concentrations of soda ash, borate, sodium sulfate, salt, and magnesium compounds; byproduct candidates include bromine and potash. Limestone from the study area could be used in recovering soda ash, boron compounds, sodium sulfate, and magnesium compounds from brine.

Markets for brine mineral products appear to be undergoing steady and strong growth, especially in the Pacific northwest and in Pacific rim countries. Soda ash and a daughter product, caustic soda, and sodium borohydride will receive increased application in the bleaching of paper pulp for environmental reasons. Soda ash, soda ash products, and boric acid are widely used in the fluxing of metals, and have important applications and markets in the aluminum industry in the northwest and the developing Chinese counterpart. Evaporite commodities are essential to many "backbone" industries, as well as to many new applications and advanced materials.

## **MINED-LAND RECLAMATION IN CALIFORNIA**

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In California, reclamation of surface mining operations are required by the Surface Mining and Reclamation Act (SMARA). It is the intent of SMARA to ensure that mined lands are reclaimed to a beneficial end use. Prior to initiating mining operations within the state, a reclamation plan must be approved. All mining operations in California, on private, state, or federal lands, that remove more than 1,000 cubic yards of material or disturb more than one acre, must have an approved reclamation plan. The reclamation plan approval process occurs at the lead agency level (usually the county or city), but the state must have an opportunity for review and comment.

Reclamation must proceed in accordance with the approved reclamation plan and, for operations with reclamation plans approved after January 15, 1993, in accordance with minimum statewide reclamation standards. The reclamation plan must specify an end use and describe how the mine will be reclaimed to achieve the end use. Minimum reclamation plan requirements are included in SMARA and the implementing regulations. Minimum statewide reclamation standards have been adopted for wildlife habitat; backfilling; regrading; slope stability; recontouring; revegetation; drainage; diversion structures; waterways and erosion control; prime and other agricultural land reclamation; building structure and equipment removal; stream protection; topsoil salvage, maintenance, and redistribution; and tailing and mine waste management.

The Division of Mines and Geology, Mined-Land Reclamation Program (MLRP) provides technical assistance to the state's approximately 130 lead agencies in the review of reclamation plans. This assistance is provided in several forms. The primary task of the group is to provide technical review of reclamation plans to assure that the minimum requirements of SMARA are met. Dissemination of reclamation information through publications is another activity in which the Mined-Land Reclamation Program (MLRP) engages. Workshops, sponsored by the group, are used as a means to better understand the needs of lead agencies and mine operators.

MLRP maintains a staff with expertise in mining, erosion control, slope stability, revegetation, in-stream mining, and sensitive species. Prior to approval, lead agencies must forward a copy of reclamation plans for review by MLRP. Depending on the technical issues addressed, the plan will be reviewed by several individuals. Review comments are provided to the lead agency in written form. The lead agency is not bound by the comments but must prepare a written explanation describing the disposition of major issues raised. When the lead agency's position is at odds with the recommendations of the state, the explanation must address why comments were not accepted.

## CANADA'S ZERO EFFLUENT POTASH MINE

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Potash is Canada's leading industrial mineral in terms of value of production, with some 12 M tonnes of muriate of potash produced in 1992 for a value in excess of \$1 billion U.S. For each tonne of potash produced, about two tonnes of waste salt is also generated, together with slimes and brine. The disposal of these waste products, particularly the salt and slimes which are discharged on the surface, has recently become an environmental concern. This concern is forcing companies and regulatory authorities to review disposal practices.

In New Brunswick, on Canada's east coast, Potash Company of America operates a mine at which 2 M tonnes of potash ore and 0.5 M tonnes of rock salt are mined each year. The mine is constructed in an environmentally sensitive area, noted for its dairy farms and salmon angling. In such an area it was recognized that the storage of waste on surface would be unacceptable, and the mine was designed around this principle.

Three main waste streams—salt, slimes, and brine—must be managed as an integral part of the mining system. About 1.5 M tonnes of fine salt tailings from the milling process and the rock salt screening operation are sent directly to the active cut-and-fill potash stopes to be used as backfill. Slimes and excess brine from the mill are piped underground as a slurry to be discharged into one of the basin shaped stopes created by mining the rock salt. While the slimes settle out, the clarified brine is withdrawn from part of the stope to be pumped to the surface as a feedstock for the evaporator—a process which recovers the contained potash values in the brine.

By designing a system which integrates the mining, processing and disposal of all product streams, and by careful production planning, it has been shown that zero effluent potash mining is possible and points the way for the industry in the future.



## BIOTECHNOLOGY AND INDUSTRIAL MINERALS\*

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Glamorous, burgeoning biotechnology and mundane industrial minerals would at first glance seem to share little in common, but in truth, modern biotechnology depends on many minerals. Biotechnical processes also can be used in industrial mineral extraction and processing. Biotechnology is broadly defined as the application of biological organisms, systems, or processes to manufacturing and service industries. Genetic engineering has reinvigorated one of mankind's oldest sciences, biotechnology, into a booming business. Many modern processes depend on microorganisms cultivated under very stringent conditions in bioreactors. Minerals from carbonate, sulfate, chloride, nitrate, phosphate, and silicate families are used to provide essential nutrients and to regulate growth conditions (such as pH) in order to assure optimal growth of organisms. Certain cells or enzymes perform better when immobilized upon or within solids, and minerals are often used to immobilize cells, especially in continuous process. Minerals are also used extensively in separating and purifying products of biotechnology. Diatomite, zeolites, and silica are especially useful in purification processes. Industrial minerals also are commonly used to clean up large volumes of process water that must be treated.

Biotechnology can be employed in exploration, extraction, and processing of geologic materials and in reducing mining or other environmental problems through bioremediation. Microbes have been shown to solubilize certain elements and so promote extraction of heavy metals, phosphate, aluminum, potassium, and even rare earth elements. In a related technique, unwanted materials such as pyrite impurities can be leached microbially to produce cleaner products in sand and clay industries. Microbial actions can modify surface characteristics and so enhance certain ceramic properties. Certain organisms can accumulate useful elements from dilute sources; others can transform unusable chemical species to more useful forms. Deterioration of stone, concrete, and even glass or brick, can be accelerated by microorganisms. Control of such biodeterioration could improve long-term performance of industrial mineral products. Microbial processes have shown promise in improving several mine-related problems. Certain bacteria help remove clays from phosphate slimes and other suspensions. Others are used to degrade cyanide or other organic chemicals such as floatation aids. Cells immobilized on clays have been especially efficacious in bioremediation.

Biotechnology industries, like the industrial minerals industries, encompass huge ranges of materials and processes. Costs of products from these industries range from pennies to thousands of dollars per unit, and their products are vital for maintaining modern life styles. Many biotechnical processes depend upon industrial minerals and certain biological processes can be harnessed to do useful tasks in the minerals field. The interplay of industrial minerals and biotechnology is important today, and as biotechnology advances, its interaction with the industrial minerals industry can only increase.

## **GEOLOGY AND MINING OF GYPSUM FROM THE MIOCENE AGE FISH CREEK GYPSUM IN IMPERIAL COUNTY, CALIFORNIA**

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The United States Gypsum Company operates a large gypsum quarry and wallboard manufacturing operation in Imperial County, California. The operation produces a variety of gypsum wallboard products, plasters and agricultural gypsum products. The manufacturing plant is located about 12 miles (20 km) west of El Centro and the quarry is located about 28 miles (45 km) northwest of the manufacturing plant. Gypsum rock is transported from the quarry to the manufacturing plant by a company-owned, narrow-gauge railroad.

Gypsum up to 200 feet (61 m) thick is exposed on the west flank of the Fish Creek Mountains as low, rounded hills with topographic relief of 250-300 feet (76-91 m). The surface of the gypsum is covered by a crust of efflorescent gypsite. The gypsum is a nonmarine unit of Miocene age and is named the Fish Creek Gypsum. The deposit is very pure with few interbedded units of siltstone and claystone. The gypsum dips westward beneath Quaternary alluvium in the Fish Creek Wash. Anhydrite occurs beneath the gypsum in the Fish Creek Wash.

The Fish Creek area is located in the Salton Trough, a rift zone and northern extension of the Gulf of California. The Salton Trough was filled by marine and nonmarine clastic sediments and minor evaporites during the Miocene and Pliocene. Evaporites were deposited in a shallow-water, deep-basin environment by seawater seepage into a restricted basin through a sill or by periodic overflow of the sill. Uplift during the late Pliocene to Pleistocene produced folding and faulting and exposed the deposit.

Gypsum is quarried by conventional drilling and blasting methods. Little to no stripping of overburden is necessary because of the excellent exposures of gypsum at the surface. The mine-run gypsum is transported by quarry haulage trucks to the primary crusher. The crushed rock is stored in a covered rock shed and loaded into railcars for transporting to the manufacturing plant. Agricultural gypsum is produced at the quarry and shipped in bulk by over-the-road trucks to various markets.

## **GEOLOGY OF THE KRAMER BORATE DEPOSIT BORON, CALIFORNIA**

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The world-class Kramer sodium borate deposit is being developed by modern open pit operations near Boron, California. The deposit is a bedded, lenticular sedimentary sequence of borax and kernite crystals together with claystone. The borates dip south into a structural basin-bounding fault and were formed in the bottom muds of a permanent shallow lake. The lake was fed boron and sodium-rich solutions from a thermal spring source of volcanic origin. In addition to deposit geology, present day geotechnical concerns such as groundwater and slope stability will be discussed.

## LABORATORY INVESTIGATIONS PRIOR TO START-UP OF VULCAN'S FRAC SAND PLANT, VOCA, TEXAS

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In the early 1980s, Vulcan Materials Company entered the hydraulic fracturing sand marketplace with superior products, trade-named Texsan, produced from the Hickory Sandstone. Development of these products started with systematic lab evaluation of the basic geologic controls and process variables on product quality. Much lab work was done with NX cores that were: 1) photographed, 2) logged in general for primary sedimentary features and in detail for cementation patterns, 3) used for response-to-disaggregation studies using lab jawcrusher, wet ball mill, and manual techniques, coupled with petrographic examinations and American Petroleum Institute (API) crush resistance tests, and 4) optimally disaggregated in 20' increments (half of the optimum production bench height) for gradation analyses. The API tests for sphericity, roundness, acid solubility, turbidity, and crush resistance evaluated how product quality changes with processing of a bulk sample in lab-scale, vertical-shaft impactor, and ball and attrition mills.

Geologic factors which affect quality of the 20/40 frac sand size are: 1) 20-40 mesh feldspar, and 2) areas of strong cementation in the sandstone that result in poorly processed product (either incompletely disaggregated sandstone or broken sand grains). A 20-foot zone above the basal unconformity with granite contains 20/40 product-size feldspar that can be eliminated by selective mining. Several types of sandstone cementation are present. Dense hematite, quartz and feldspar cements make the sandstone more difficult to disaggregate, thereby affecting quality. Quartz and feldspar cements are abundant at the base of the formation, while the dense hematite cementation which has a hollow sphere or bed-controlled pattern, tends to occur about 70-100 feet below the land surface. The basal cementation zone can be eliminated during the selective mining to prevent contamination with weak feldspar. The dense hematite-cemented sandstone is eliminated by discarding oversize material after vertical shaft impact processing of the raw sandstone feed to the plant. The weaker cements of diffuse hematite, goethite, and clay do not affect the quality of the processed sand product.

API frac sand specifications for crush resistance (max 12 % loss) can be met by blending. In the laboratory, about two thirds of the deposit yields a 20/40 size sand that easily passes specifications with about 7-9 % loss. For 40 to 70 feet above the basement rocks the sandstone yields sand with 13-14 % loss that can be blended with the better quality sand to make a product that meets all specifications.



# WASTE MATERIAL RESOURCES IN VIRGINIA

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Mining-related wastes, which are increasing, are being utilized more as resources in Virginia. The Environmental Protection Agency (EPA) has divided mining-related wastes into two categories: mineral extraction and beneficiation and mineral processing. Materials from both categories are in Virginia, where waste (by-product) materials are present at numerous mining sites/processing plants; some of which have been exploited for various uses in the past and/or present. These materials include: used concrete recycled for roadbase material, by-product pyrite coated with magnetite for use in portland cement, minor amounts of fly ash for use in concrete block, lightweight aggregate and flowable structural fills, granite and diabase quarry fines for use as agricultural material and as asphalt filler, lime kiln dust for use in neutralizing and stabilizing coal refuse, soapstone aggregate for use in terrazzo heat retention panels, kaolin used as a filler product and as an ingredient in white cement, slate quarry fines used as landcover, with aggregate for crusher run and as a filler in asphalt, and coal refuse used for fuel in a lightweight aggregate plant. There are some materials that were never utilized as a resource, although numerous ideas were investigated, such as a high-alumina scrap produced as a by-product at a ferrovanadium processing plant. However, large quantities of by-product (waste) materials from metal mining, industrial mineral and fossil fuel operations remain to be disposed of in an environmentally safe and economic manner.

In 1989, almost one million tons of fly ash were produced from coal burned at eight coal-fired power plants in Virginia. Present uses for this waste such as an ingredient in concrete block, concrete aggregate and in structural fills cannot dispose of all of the available material; however, increased use as a soil/rock substitute for structural fills and embankments may be part of the answer. Another waste (by-product) material is calcium carbonate precipitate paste produced at a lithium carbonate processing plant and presently being put into an on-site inactive underground limestone mine.

As we move toward the year 2000, flue gas desulfurization (FGD) wastes in the form of  $\text{CaSO}_4$  will probably increase three-fold. If this material contains a minimum of 95 percent gypsum and negligible chloride, it may have a value to a wallboard producer. Thought has to be given how this increasing waste can be disposed of in an environmentally safe manner.

# GENESIS OF BARITE DEPOSITS IN THE CENTRAL MOJAVE DESERT, SAN BERNARDINO COUNTY, CALIFORNIA\*

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Barite in the central Mojave Desert occurs in a variety of geologic settings. The barite deposits of greatest economic interest occur in early Miocene intermediate to silicic volcanic rocks. These deposits most commonly occur as northwest striking, steeply dipping veins a few centimeters to several meters wide. In addition barite occurs in superjacent middle Miocene pelites and volcanoclastic rocks where, with a few exceptions, the barite most-commonly has been deposited in small veinlets or disseminations. The veinlets are randomly oriented. The few large veins in the middle Miocene rocks have attitudes similar to the veins in the early Miocene volcanics. Steeply dipping, northwest striking veins of barite also are present in the varied assemblage of metamorphic basement rocks stratigraphically below the volcanics. A regional low-angle normal fault, inferred to have formed contemporaneously with the early Miocene volcanic rocks, separates them from the basement.

Associated with the barite in both types of Miocene host rock is slightly later quartz and silver. This is accompanied by magnetite and manganese oxides, and late-stage calcite mineralization. Sporadic, weakly developed propylitic alteration envelopes have been recognized in thin section from some veins. Silicification is often localized where later movement along structures created dilatant environments accommodating fluid movement. Previous work yielded a 17 MA age for the alteration.

Fluid inclusion data from the volcanic-hosted barite in the Calico Mountains indicate mineralizing temperatures ranging from 250° to 300° C. Salinities average about 6.5 weight percent NaCl. Temperatures from the stratigraphically higher sedimentary rock-hosted barite ranges from 185° to 195° C. Salinities range from 4-5 percent NaCl. Volcanic-hosted barite from veins in the Waterman Hills approximately 15 kilometers west of the Calico Mountains sites yield temperatures averaging about 190° C. Kinematic indicators suggest two discrete strain events are associated with vein emplacement, an earlier extensional episode creating fracture systems into which vein minerals were introduced and a later strike-slip event in which some of the earlier fracture/veins systems provided zones of weakness facilitating right-slip strain, notably along the Calico Fault.

The close regional spatial association of the regional normal (detachment) fault and the various sites of barite mineralization, the attitudes of the barite occurrences, their age and temperatures are suggestive of a causal relationship between the extensional event and the mineralizing event. Typical of many lower plate environments in extended terrain is pervasive chloritization of the materials immediately below the surface of detachment. It is suggested that intense shearing along the detachment fault causes the generation of hydrothermal fluid phases which swept along stress/temperature gradients in the affected rock leaching various elements which then were transported upward and deposited in the open space available in shallower environments.

## INTRAVENOUS GEOLOGY

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A few years ago during a Southeastern Geological Society field trip, a professor from a Florida university and a trip leader said at one of the stops, "... and for those of you interested in the geology, ect..." More recently, in the spring of 1992, a geology faculty member at another southeastern university remarked, "Field geology is obsolete." An interviewee for a potential assistant position stated that he had never had a field class. This would-be assistant was to receive his Master's Degree in Geology within a few days from yet another southeastern university. A regional illness? Certainly not, but symptomatic of the general health of Geology.

Capitulation to Environmental Sciences seems to be in vogue with Geology becoming a four-letter word and the mention of mining is verboten regardless of the company.

These trends permeate our profession while the demands for earth materials increase, often exponentially. Efficiency, a word lost on government, is routinely expected of business—our business—the industrial minerals geologist and producer. Our stage shrinks but the responsibilities expand. Are we meeting the challenge? Stay tuned!

## FLAKE GRAPHITE AND ZEOLITE RESEARCH PROVIDES POTENTIAL SOLUTIONS TO DOMESTIC PROBLEMS

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A current U.S. Bureau of Mines mining and minerals research effort is addressing the recovery of flake graphite from kish, a steelmaking waste product, and the use of zeolites from abundant domestic natural deposits for efficiently cleaning up mining industry wastewater.

The U.S. is almost totally dependent on imports for its graphite needs, but this may change depending upon the results from a pilot plant being constructed by industry using Bureau technology. Standard mineral processing techniques were applied by the Bureau to recover high-quality flake graphite from kish. It was considered novel enough to receive an R&D 100 Award in 1992, and its commercialization has the potential to supply the total U.S. demands for graphite many times over.

Zeolites have ion exchange properties similar to ion exchange resins, but are less expensive and available in large quantities. Samples of naturally occurring zeolites were tested for their efficiency in removing metal ions from synthetic and industrial waste solutions. The tests focused on defining their selecting, loading, eluting, and regenerating characteristics, and on developing a method for recovering the metal ions as added value products. The results showed that the removal of metal ions with zeolites from particular solutions is feasible and that this technique has the potential for being used in an integrated chemical treatment systems approach either as a primary or secondary cleaning step.



# GEOLOGY AND PHYSICAL PROPERTIES OF SOME ACTIVE AND POTENTIAL SOURCES OF INDUSTRIAL AND PET WASTE ABSORBENTS IN THE UNITED STATES\*

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Most producers of industrial and pet waste absorbents are grouped by the U.S. Bureau of Mines under the category "Clay: Fuller's Earth." About half of the fuller's earth produced in the United States comes from the Meigs-Attapulugus-Quincy district of Florida and Georgia. This district yields montmorillonite and attapulgite clays. In Illinois, Missouri, Tennessee, and Mississippi montmorillonite is produced from the Porters Creek Formation. In Oregon, Nevada and Arizona absorbents have been produced from 1) zeolitic bentonite, 2) lacustrine diatomite interbedded with bentonite and volcanic ash, and 3) volcanic ash. In California, fuller's earth absorbents and similar products have been produced from diatomite, diatomaceous shale, siltstone, tuff, pumice, zeolites, and weathered plutonic rock.

In 1990, the authors compiled a national list of producers of absorbents. Out of the nineteen companies which were contacted, ten provided samples of their product and crude "ore," and several supplied descriptions of testing procedures for their product. The consensus of the interviewed companies was that the most widely used testing procedure was U.S. General Services Administration (GSA) Specification P-A-1056B.

This specification tests resistance to attrition, granule size, ability to absorb lubricating oil, ability to absorb distilled water and solubility in distilled water. The constitution of absorbent granules must be such that they 1) will not breakdown when walked on, 2) have relatively uniform size, 3) are able to absorb oil and water, and 4) will not dissolve in water. In addition to these tests we determined the bulk density of the material.

The material provided to us was tested using the procedures in GSA Specification P-A-1056B. Additional samples of clay, pumice, welded tuff, diatomaceous shale or siltstone were collected by BLM staff within Inyo and Kern counties, California. Thirty-four (34) samples were analyzed. The crude "ore" and locally collected samples were crushed and sieved to collect the material passing 4 mesh and retained on the 40 mesh screen. This 4/40 fraction was allowed to air-dry. One surprising finding was that the Bishop Tuff has excellent absorbency and high resistance to attrition. The results of this study are summarized in the following table:

TEST	FINISHED PRODUCT		CRUDE "ORE"	
	MAXIMUM VALUE	MINIMUM VALUE	MAXIMUM VALUE	MINIMUM VALUE
BULK DENSITY (lb/ft <sup>3</sup> )	75.0	23.0	68.0	26.0
ATTRITION (weight percent)	89.1	.1	98.0	.3
OIL ABSORBENCY (ml/g)	1.2	.2	1.3	.3
WATER ABSORBENCY (mg/g)	1.2	.5	1.5	.5

## THE CALIFORNIA MINERAL EDUCATION FOUNDATION CONFERENCE MODEL: CHANGING PUBLIC PERCEPTION OF THE MINERAL INDUSTRIES

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Few members of the general public have a clear understanding of mineral resources. Most people do not know how minerals are mined or why they must be extracted from many diverse locations. Many people acquire knowledge of mineral development from mass media sources with incomplete details or obvious anti-mining bias. The California Mineral Education Foundation was formed in 1991 to provide educational opportunities for the public and industry.

Changes in earth science teaching requirements for K-12 curricula have been major since the passage of California Senate Bill 813 in 1983. Model graduation standards, curriculum standards and the state science framework mandate substantial coverage of geoscience topics. The California State Commission on Teacher Credentialing has completed changes in multiple subject and single subject science credentials which will require more geoscience preparation for all teachers. The need for pre-service and in-service education in geoscience is at an all time high. Teachers must have continuing education to maintain their credentials and many are now seeking information in geoscience.

The California Mineral Education Foundation designed and conducted the California Mineral Education Conferences held in August 1991 and 1992. The program involved lectures and field trips on mining geology environmental problems and political concerns. Master teachers were employed to share how they get across mineral resource concepts in the classroom. Ninety-six percent of the participants stated that they had changed to a more positive perception of mining after taking the three day course.

## PALEO MOLASSES—THE FORGOTTEN INDUSTRIAL MINERAL

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Two occurrences of a shale containing a sugar-based (?) substance have been reported. In the 19th century, one occurrence in England was developed. A shaft was sunk, drifts developed, and a processing plant and railroad constructed. "Paleo molasses" was introduced to the English market. The history of the development of this unique "industrial mineral" occurrence is discussed.

## **PUMICE FOR STONE-WASHED AND ACID-WASHED JEANS FROM BLIND SPRINGS HILL, CALIFORNIA**

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The Blind Springs Hill pumice beds are located 5 miles SW of Benton, California in the foothills between the Benton mountain range and Blind Springs Valley. The best exposures of the pumice are in an area 0.75 miles west of Blind Springs Hill. The pumice is Quaternary ejecta material which came from the rhyolitic volcanoes in the Glass Mountain-Volcanic Tablelands area of Mono County. The pumice beds occur in two distinct layers separated by an unconformity. The upper layer is 0 to 11 ft. thick and consists of coarse subangular pumice fragments, some of which are over 1.75 inches in diameter. The lower bed is medium to coarse grained with subangular fragments up to 1.0 inch in size. The lower bed is 0 to 9 feet thick. Overburden at the Blind Springs Hill deposit varies from 0 to 15 feet. There are approximately 1 million cubic yards of material in the deposit that can be mined.

The size distribution in the deposit is mostly fine with only 10.6% of the pumice fragments being over 0.5 inch in diameter, the minimum size needed for stone-wash or acid-wash applications. Suitability of pumice for the textile industry is quantified by standard 15-minute abrasion and absorption tests. In the Blind Springs Hill deposit, the plus 0.5 inch fraction has an abrasion loss of 33% which is too high for stone-wash application but it has an absorption capacity of 36% which makes it suitable for acid-wash applications in the textile industry. The abrasion and absorption properties of this deposit are within the range of those which have been measured for other pumice deposits within the United States.

## **DEVELOPMENT AND GEOLOGY OF THE HECTOR CALIFORNIA CLAY DEPOSIT**

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Situated in the Mojave Desert of San Bernardino County, California the unique Hector Mine deposit is a hydrothermally alteration clay within late Tertiary lacustrine accumulations. Associated fumarole activity that deposited contemporaneous travertine has been theorized to be the causative mechanism in the genesis at this aluminum deficient smectite clay.

Continually mined for over one-half a century, development began as a small underground operation. Open pit methods were eventually used to meet the increasing demand for this high quality thixotropic clay. Seam deformation caused by the adjacent and still active Pisgah fault coupled with a thick basalt cover from the Quaternary Pisgah Crater has complicated the mining process.



# THE MOJAVE DESERT PROVINCE, SOUTHERN CALIFORNIA: GEOLOGIC OVERVIEW

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The Mojave Desert province is comprised of a diverse group of mountains that range in elevation from about 2,000' (600 m) to 3,000' (900 m), separated by tracts of alluvial cover. The province is bounded on the southwest by the San Andreas fault, on the north by the Garlock fault, on the east by the Death Valley Granite Mountains fault zone, and on the south by the Pinto Mountain fault. Rocks preserved in the Mojave Desert Province collectively record a rich assemblage of Precambrian crystalline basement ranging from 1.87 to 1.2 Ga, upper Precambrian and Paleozoic Cordilleran miogeoclinal sediments and platform rocks, Mesozoic backarc and interarc shallow marine and continental sequences, locally emplaced Permian-Triassic syenitic plutons, extrusion of hypabyssal volcanic rocks of the ?Jurassic "Sidewinder Volcanic Series" and regionally intruded late Mesozoic granitoid batholithic rocks.

The Mojave block apparently was a high-standing element for much of the early Tertiary, with strata of Late Cretaceous or early Tertiary age preserved only on its margins.

Beginning about in the late Oligocene, an intense episode of regional north-south extension was developed in a roughly eastwest belt that traversed the central part of the province. This has been termed the Mojave Rift. The extensional regime lasted from about 22-17 m.y., and is generally divided into two phases. The first, from about 22 to 20 m.y., records intense extension via the activity of crustal-scale, simple shear, low-angle normal faults, high-angle normal faults and extension fracturing along with intrusion of intermediate to silicic volcanic rocks, including episodes of explosive volcanic activity. The Peach Springs Tuff, a major regional marker unit that extends across the Mojave from Arizona to about Barstow forms an effective stratigraphic lid on the extension interval, and is dated isotopically at about 18.5 Ma.

The extension episode was followed by an interval of high angle normal faulting and dike emplacement from about 19 to 17 Ma, and was accompanied by at least local uplift and volcanism. Most volcanoclastic and epiclastic sedimentary units of the central Mojave block post-date the interval of extension and normal faulting, and occur as a complex of marginal alluvial and more interior lacustrine facies that formed as recently as Pleistocene, at least locally. Paleomagnetic and isotopic studies indicate a complex history of crustal rotations, distributed across a number of discrete domains occurred in the past 10 Ma and likely still is underway. Some of the youngest volcanic and geomorphic features of the province apparently developed at "holes" formed at the edges of rotated blocks.

## HOW SPECIAL ARE SPECIALTY SANDS?

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Sand is a ubiquitous naturally occurring material resulting from the physical and chemical breakdown of rocks. The definition of sand varies, as do the number of products made from the material, but it is generally defined as a loose, granular and non-cohesive material consisting of one or more minerals. Sand is generally classified by grain size, however, the measurements or scales differ depending on the context in which it is being used.

Sands can be broken down into two categories: specialty sand and construction sand. Specialty sand is generally a term given to a product made of a single mineral such as quartz, olivine, zircon, feldspar, staurolite or chromite. In most cases, processing is necessary to achieve this mineralogy. Some types of specialty sand have proven to be invaluable to a number of industries, including iron and steel foundries and glass manufacturers. These industries rely on specialty sand because it conforms to rigid specifications.

Construction sand, however, generally consists of more than one mineral and cannot conform to stringent specifications. As a result, the range of markets for construction sand is much smaller than that of specialty sand, and its uses are limited. The differences between specifications, processing, marketing and uses will be discussed in this paper, with emphasis placed on silica and construction sand.

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